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The Geological Society of America

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NEW EVIDENCE OF THE ORIGIN OF PRE-CAMBRIAN CARBON

BY KALERVO RANKAMA

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ABSTRACT

An investigation was carried out concerning the origin of carbon in the following pre-Cambrian materials from Finland: graphite, carbon-bearing schists, carbonaceous accumulations in phyllites including the suggested fossil *Corycium enigmaticum* Sederholm; shungite from Karelo-Finnish S.S.R. Geological and petrological descriptions of the materials investigated are given. CuO, V_2O_5, and MoO_3 contents of the samples and the isotope ratios C^{12}/C^{13} in carbon extracted from same are presented. Geological evidence and trace-element determinations make probable the division of carbon in these samples into organic and inorganic groups; the mass spectrometric C^{12}/C^{13} determinations furnish definite proof of this and also final proof of the organic nature of the *Corycium* which thus is a real fossil of the Late Archean time, the oldest ever recorded with definite certainty.

ACKNOWLEDGMENTS

The author is much indebted to Professor Alfred O. C. Nier, of the Department of Physics, University of Minnesota, who very generously carried out the C^{12}/C^{13} determinations, thus providing material for the most critical part of the investigation, and to Mr. K. J. Neuvonen, M.A., who ably carried out the enrichment and combustion work of carbon at the Institute of Chemistry, University of Helsinki, Finland. Mr. Antti Auterinen, M.A., of the above Institute, supplied expert advice on the combustion methods.

Mr. Oiva Joensuu, M.A., and Mr. Jouko Vuojela carried out the spectrochemical work at the Geochemical Laboratory of the Institute of Geology, University of Helsinki. Mrs. Toini Mikkola, M.A., carried out some checks of feldspar determinations in thin sections at the Laboratory of the Geological Survey of Finland. Thanks are due to all these persons for their kind assistance.

The Geological Survey of Finland has allowed the use of original photographs of *Corycium* from its archives. The Geological Society of America has given material support in the form of two research grants. The author wishes to extend his thanks to these organizations for their assistance.

Finally, the author wishes to express his gratitude to his wife, Mrs. Riti Rankama, for her assistance during the field trips to the *Corycium* localities at Aitolahti.

INTRODUCTION

The question of the primordial life, the fauna and flora of pre-Cambrian times has, for a long time, cast a magic spell on the minds of geologists and paleontologists. Truly, we may share the opinion of Raymond (1935, p. 375):

> "So anxious are geologists to obtain fossils from these rocks that anything which remotely resembles an organism is carefully saved and studied in the greatest detail. . . .No recently discovered 'Old Master' is subjected to more critical scrutiny or to more acid tests than is a 'find' from rocks older than the Cambrian."

The existence of life at least in Middle pre-Cambrian times seems to be certain. Evidence concerning the fossiliferous character of the pre-Cambrian is sought in the reported discoveries of fossils and in the presence of graphite in pre-Cambrian formations. Thus far, the pre-Cambrian remains of animal activity, represented by

actual fossils more generally accepted by geologists, may be divided into four groups: blue-green algae, brown algae, siliceous sponges, and segmented "worms". Nearly all of these are found in Algonkian formations, most of the finds having been made in North America. We may here recall the Algonkian algal flora of the Belt series, discovered by Charles D. Walcott and more recently restudied by Fenton and Fenton (1936). Since the structures of *Eozoon canadense*, *Aspidella terranovica*, *Atikokania lawsoni* and *A. irregularis* have been proved to be of inorganic origin, the role of the so-far oldest remains of life may be attributed to the calcareous algae of the genus *Collenia*, described by Fenton and Fenton (1939, p. 91) from the Northwest Territories of Canada. According to these authors the species of this genus (*Collenia septentrionalis*, and others) occur in Early or Middle pre-Cambrian dolomites associated with dolomitic sandstone, probably Early pre-Cambrian (Archeozoic). In addition, these authors have found what they interpret as algae or colloidal bodies in cherts on Mystery Island, Echo Bay, Great Slave Lake. The cherts, by the lead-uranium ratio age determinations made of the pitchblende veins cutting them, belong to the Late Keewatin (1939, p. 92).

The presence of graphite in pre-Cambrian formations has frequently been cited to support the view of organic activity. With due consideration to E. S. Moore's and A. N. Winchell's explanations regarding the inorganic sources of carbon and its mode of deposition from magmatic gases, many American geologists, at all events, seem to consider a part of the graphite at least to be of organic origin (*cf.* Walcott, 1899, p. 227; Wilson, 1939, p. 305; Pettijohn, 1943, p. 948). On the other hand, as pointed out by Hawley (1926, p. 442) and Wilson (1931; 1939), the evidence furnished by graphite is only a probable, not a positive, indication of the existence of life in the pre-Cambrian, and, according to Hawley (1926), this statement is valid for the evidence of the Archean life in general, since organiclike structures of inorganic osmotic origin open up possibilities of misinterpreting filamentous forms as fossils.

These views regarding graphite are readily shared by Finnish colleagues. In addition, the latter commonly believe that the graphite- and pyrite-bearing schists and slates met in Early through Late pre-Cambrian formations are of bituminous and sapropelic origin (Eskola, 1938, p. 347); this belief is shared by Pettijohn (1943, p. 948) as to the carbon-bearing slates and graywackes of the Canadian Shield. To sum up the available information, though the occurrence of lower forms of vegetal and animal life has been proved in the later pre-Cambrian times, the absolute proof of the existence of life in the Archean has still been wanting. Some sceptics, like Conway (1945, p. 601), suggest that no multicellular animals were developed until Late pre-Cambrian times.

In 1897 the eminent Finnish geologist, J. J. Sederholm, in his classic paper on the Tampere[1] Region described peculiar cell- or sausage-shaped small sacs, black from finely disseminated carbon, occurring in Bothnian phyllites on the shores of Lake Näsijärvi near the city of Tampere, and detected by him in 1890. These carbon sacs were believed to be the remains of primitive plants. Sederholm reverted to his findings in 1909, from which year dates his description to the General Geological

[1] The Swedish form of this name is Tammerfors.

Map of Finland, Map of Rocks, Sheet Tampere, published (in Swedish) in 1911. He decided (1911, p. 28) to give them the name *Corycium* (from κορύκιον, small sack) *enigmaticum* believing them to be, after years of consideration, real Archean fossils, perhaps algae. The question of *Corycium* evidently remained among the subjects to which Sederholm gave his most wholehearted devotion, and we may trace his further observations on these formations in many of his later papers. Numerous geologists the world over were able to see the *Corycium* sacs during excursions to the Tampere region under his enthusiastic guidance.

Sederholm also had to defend his *Corycium* (1924; 1925a) against attacks by Krejci-Graf (Krejci, 1924; 1925) to interpret these formations as being of inorganic tectonic origin. Up to his death he remained firmly convinced of the organic origin of his find.

SCOPE OF THE WORK

The present author became interested in the *Corycium*-bearing phyllites during a visit to the area in 1938. More detailed investigation was carried out during visits in the summers of 1941 and 1945, and final checks of the field observations were made in 1946. In 1941, due to the low water in Lake Näsijärvi, rock surfaces normally more than 1 meter under water were profitably studied. First, it was decided to attack the problem of the origin of the *Corycium* by a spectrographic analysis of some of its trace constituents: Cu, V, and Mo, all important for organic processes in Nature and, together with Ni, Ag, and W, associated with petroleum and asphalt and also with bituminous shales, as is stated by Goldschmidt (1944, p. 3). However, these elements do not deliver absolute proof because of their possible inorganic sources. For example, vanadium may be reduced to V^{3+} ions by inorganic processes and thus be enriched in the hydrolyzate sediments by adsorption. Accordingly, results of modern research on the isotopes and the variations in their relative abundances were noted.

Important studies of the variations in the relative abundance of the carbon isotopes have been more recently carried out by Nier and his co-workers. Variations in the C^{12}/C^{13} abundance ratio of carbon obtained from various natural sources were established (Nier and Gulbransen, 1939), and it was shown that the isotope C^{13} is concentrated in the limestones while the plant forms prefer the lighter isotope, C^{12}. These results were confirmed by Murphey and Nier (1941), and, in addition, their results appeared to deny the presence of an age effect in spite of the versatility of the material investigated, pre-Cambrian to Recent limestones, Carboniferous through Pliocene coals, and Late Pleistocene to Recent wood being included.

The discovery made by Nier and his co-workers is very important and hereby is a powerful tool placed in the hands of geologists for appropriate use. Wickman (1941) has been the first to use it to calculate the total amount of coal and bitumen. As he said this discovery affords the possibility of determining whether or not the carbon in pre-Cambrian sediments is of organic origin, and thus contributes to the problem of the start of life on our globe.

Since the results of the determination of the C^{12}/C^{13} ratio evidently are apt to

furnish conclusive evidence as to the origin of *Corycium*, the author, with the assistance of Mr. K. J. Neuvonen, went to work to separate the coaly matter of *Corycium* and to convert it to barium carbonate for future mass spectrometric determinations.

FIGURE 1.—*Location of samples. 1–10*
Numbers refer to those in Table 2.

For reference purposes, samples were included of other carbonaceous materials in the pre-Cambrian of East Fennoscandia. The location of the samples is shown in Figure 1.

DESCRIPTION OF THE MATERIAL INVESTIGATED

GRAPHITE FROM PARAINEN

Two different kinds of graphite are present in the crystalline calcitic limestones at Parainen (Pargas) in southwestern Finland which belong to the Katarchean Sveco-Fennian mountain chain, *viz.* graphite crystals embedded in crystalline limestone and graphite masses at the contacts of the pegmatite veins intersecting the limestone.

A sample of the latter graphite from Ersby at Parainen was selected for the present purpose from the collections of the Institute of Geology, University of Helsinki.

According to Laitakari (1925, p. 65), the graphite disseminated in the limestones in Finland seems to originate usually from the carbon present in the primary sedimen-

tary limestone, thus being sedimentogeneous and, in many cases at least, of organic origin. The graphite at the pegmatite contacts, on the other hand, has been produced by the reduction of CO_2 contained in the calcium carbonate (Laitakari, 1925, p. 69). Experiments carried out by Frauenfelder (1924) strongly support the origin of the graphite by reduction in some cases. Rather conclusive field evidence is presented already by Wilson (1919, p. 28) in the case of graphite deposits in the Ottawa Valley, although their derivation directly from the igneous rocks intruded in the limestone must, according to Wilson, also be considered, as in the case of the Port Elmsley deposits in Ontario (1918, p. 42). Wilson (personal communication, 1947) states that most of the graphite in the Grenville region of the southeastern Ontario and the southern Laurentians of Quebec is associated with contact metamorphic deposits, a relationship suggesting that the graphite may have been derived from the carbon dioxide of the limestone.

The graphite deposits of Ceylon, according to Wadia (1943, p. 18–20), have been formed from limestone absorbed by intrusions of charnockite and related igneous rocks, whereby various calcium silicates were produced and CO_2 was dissociated to produce carbon or reduced to graphite in the presence of hydrogen.

CARBON-BEARING PHYLLITES FROM THE TAMPERE BELT

General description of the phyllites.—The peculiar shapes which, according to Sederholm, suggest the presence of life in the Archean occur in Bothnian phyllites on the east shore of Lake Näsijärvi in the Tampere Region. Description of the *Corycium* and its occurrence is based on the facts presented by Sederholm (1897, p. 81–93; 1911, p. 19–28; 1912, p. 516–18; 1924, p. 717–18; 1925a, p. 360; 1925b, p. 34; 1930, p. 13–15; 1932, p. 12), and completed with some more recent observations of the present author.

The Bothnian schists belong to the Younger Archean rocks of Cycle II according to the classification presented by Sederholm (1930; 1932), and they occur in most typical form at Lake Näsijärvi near Tampere. According to the correlation presented by Gevers (1934), the Bothnian formations should correspond to Grenville, being somewhat younger than Keewatin. The schist series is approximately 12 km thick and contains supercrustal rocks with the most indisputable original character of true sediments, *viz.* metapelitic and metapsammitic rocks, graywackes, and conglomerates. The degree of metamorphism in these rocks is quite low although their layers lie now in a nearly vertical position. The general strike of the formation is from east to west, and the dip is usually 85°–90° N. No strong folding phenomena can be established. The phyllites and mica schists, the oldest members of this series, are interpreted by Sederholm as metamorphosed silts and clays, and they show a very regular bedding, in part also cross-bedding. The phyllite formation alone is at least 2000 m thick. Intercalated with the phyllites occur metamorphic volcanic rocks, originally rhyolites, andesites, and basalts.

The most typical phyllites of this area are found on both shores of Lake Näsijärvi: in the West in the parish of Ylöjärvi and in the East in Aitolahti and in Teisko. Megascopically, they are dark gray or nearly black displaying a well-developed schistosity, sometimes foliation. Their graded bedding is due to the alternation of dark layers rich in mica with lighter-colored ones containing more quartz and feldspar.

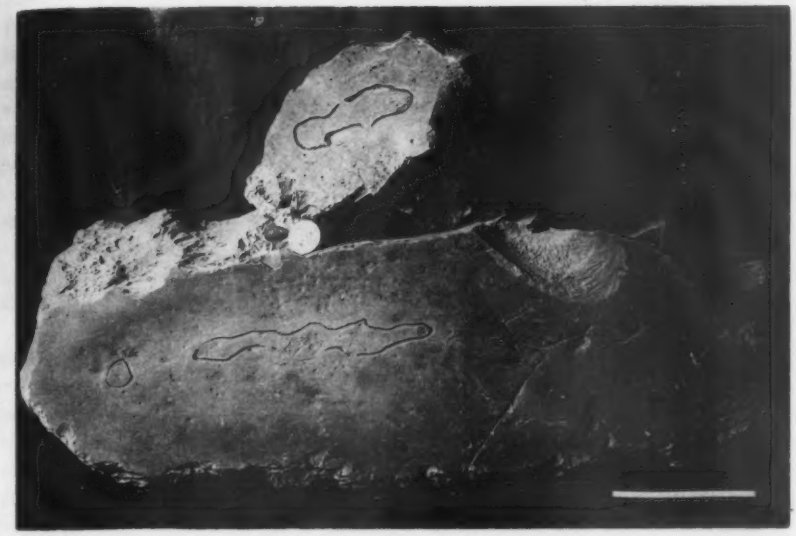

FIGURE 1. *Corycium enigmaticum* SEDERHOLM
Hand specimens at the Geological Survey of Finland. Length of scale 10 cm. Photo: Geological Survey of Finland (No. 4660).

FIGURE 2. *Corycium* (1)
Tähtinen, Aitolahti. Length of scale 10 mm. Photo: K. R.

CORYCIUM HAND SPECIMENS

FIGURE 1. *Corycium* IN PHYLLITE
Tähtinen, Aitolahti. Photo: K. R.

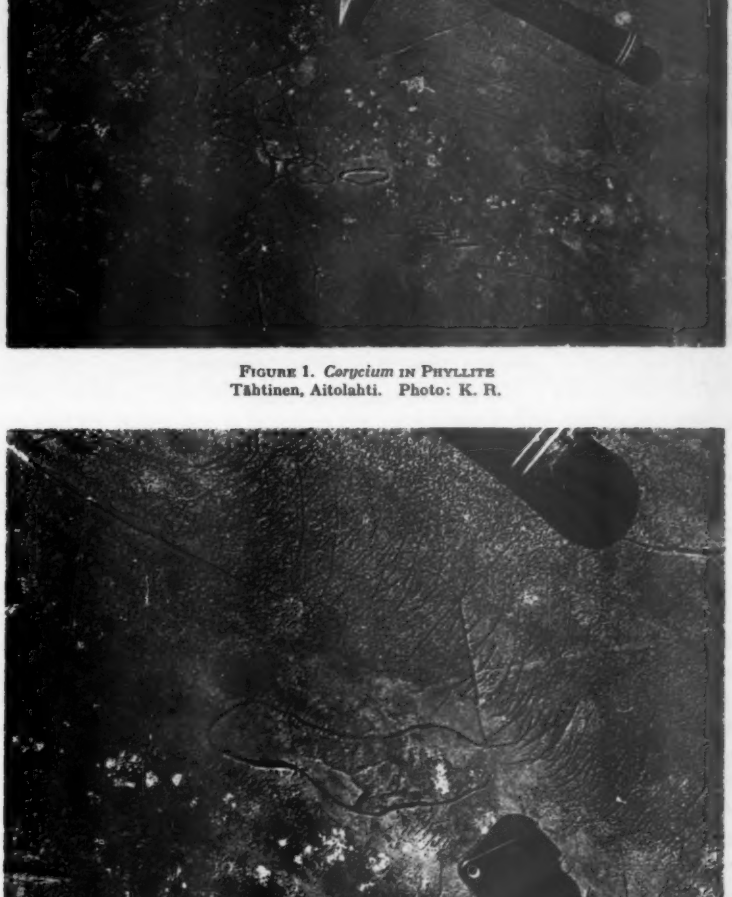

FIGURE 2. *Corycium* IN PHYLLITE
Enlarged portion of Figure 1. Length of scale 20 mm. Photo: K. R.

CORYCIUM IN PHYLLITE

Under the microscope the phyllites, according to Sederholm, are found to consist mainly of quartz and biotite with finely disseminated carbon in varying amounts. In the coarser-grained parts the biotite and quartz grains measure up to 0.01–0.02 mm while the fine-grained parts consist of a microcrystalline "paste" impregnated with quartz. The latter parts, in particular, contain much finely divided carbon, especially in the form of sharply defined separate layers less than 1 mm thick. The rock also contains much ottrelite.

The rocks described above occur in Ylöjärvi while on the eastern shore of the lake the degree of metamorphism is somewhat higher.

Here, especially south of the village Aitoniemi, the outcrops along the shore display beautifully developed graded bedding in the schists. This phenomenon can also be discerned under the microscope.

The matrix cementing the coarser quartz and feldspar grains consists of small quartz grains and flakes of biotite, a little chlorite, and finely disseminated carbon in varying amounts; in some cases, the matrix is nearly all carbon. Muscovite and, rarely, actinolite are present as accessory constituents. The coarser mineral grains of the rock may attain a diameter of 1 to 1.5 mm, in some cases up to 5 mm. They are often distinctly rounded, and the original clastic texture of the rock is neatly preserved. In most cases the quartz shows a weak undulatory extinction being, however, nearly free from strain effects.

Orthoclase and oligoclase are rather abundant, in subangular fragments, usually clouded due to alteration into muscovite and epidote. The feldspars are often replaced by biotite in recrystallizations during regional metamorphism.

Fragments of porphyritic volcanics are also abundant. Angular phyllite fragments and, occasionally, dark-gray glossy slate fragments very rich in carbon are also met, the latter in the coarser-grained layers, rich in quartz and feldspar.

These rocks have been interpreted by Sederholm as leptitic phyllites alternating with schists of phyllitic character. Chemical analyses made separately of the different layers display a typical argillaceous composition.

Carbonaceous accumulations in phyllite.—A few kilometers northeast of Tampere, in the parish of Aitolahti, a small rocky phyllite peninsula is pushed into Lake Näsijärvi, in Sederholm's times known under the name Ajonokka, this name being forgotten ever since. The shores of the peninsula, now strewn with summer cottages and bungalows, can be reached from Tampere by a tiny coastal steamer calling at a pier at Myllyniemi on the north shore of the peninsula. Half a mile along the shore to the southwest of Myllyniemi, near the villa Tähtinen, the peculiar forms of *Corycium enigmaticum*, now preserved under the protection of the law, are found on the cliff surfaces. *Corycium* and other carbonaceous accumulations are found in the rocks along the shore, but, near the villa Vaarinniemi at Alanen, a little more than 1 km southeast of Tähtinen, a finely foliated actinolite-bearing phyllite zone is met with. Still farther southeast are even more highly metamorphosed schists; 1 km south of the pier at Alanen there is a finely foliated grayish-green chlorite-biotite schist. *Corycium* is no more found in these types.

According to Sederholm, *Corycium*-bearing phyllite boulders have been found at Lielahti, just to the west of Tampere.

Three different categories of carbonaceous accumulations may be distinguished in

the phyllites, *viz.* (1) the *Corycium* proper, (2) irregular dark-gray glossy slate fragments very rich in carbon, and (3) lenticular or rounded bodies of carbon-bearing calcareous schist which often disintegrate due to weathering, leaving only cavities in the phyllite.

Corycium enigmaticum SEDERHOLM: *Corycium* proper is described by Sederholm as sharply defined carbon stripes forming more or less complete rings, either circular or elongated, on the rock surfaces. In vertical sections they have annular or tubular forms and are best described as small sacs, sometimes sausage-shaped, or somewhat similar to the spadix of the water-arum (*Calla palustris*), often as if creased, or crumpled. If elongated, their longer axis is always parallel to the bedding.

On the rock surfaces (Pl. 1, figs. 1, 2; Pl. 2, figs. 1, 2) the carbon stripes forming the rings are usually weathered to a depth of 1 to 2 mm. On a fresh surface they consist of glossy carbonaceous matter, 1 to 2 mm thick. Under the microscope, these layers are very sharply defined, of uniform thickness, containing enough carbon to form, alone, the matrix between the larger mineral grains as is seen from the photomicrograph published by Sederholm (1897, p. 92; 1911, p. 27), and from those reproduced on Plate 3, figures 1, 2.

According to Sederholm the sacs lie principally embedded in a certain bed, 10 cm wide. They are often found scattered in irregular trains in one or two layers, and may be traced at a range of 10 to 20 m, whereas the surrounding layers are nearly completely devoid of the sacs. Sometimes they are penetrated by thin veins of volcanic material, formed during the deposition of the original sediments. They may, exceptionally, measure up to 30 cm long but usually only 2 to 3 cm. The small sacs, always nearly perfectly annular in shape, are most common. Also they are usually somewhat elongated.

The *Corycium* sacs are commonly closed, but some are open on the sides with the carbon line on the rock surface resembling a spiral.

The above description by Sederholm pertains principally to the larger sacs. The more frequent small sacs were observed by the author during a detailed investigation.

At Tähtinen the *Corycium* sacs occur in four different layers at least, usually forming in them irregular trains along certain horizons.

In the northernmost layer only a few sacs are distinguished, scattered near the borders. This layer is approximately 20 cm thick. The carbon sacs are oblong ellipsoids with a maximum length of 21 mm.

The following layer to the south is about 30 cm thick and contains more sacs, rounded or ellipsoidal with a maximum length of 30 mm.

The next layer is approximately 120 cm thick. Here more than 20 *Corycium* sacs were counted on a strip of 7 m, usually forming groups or trains of several sacs. The maximum length of the rings was 115 mm. The main part of the sacs at Tähtinen is found in this layer, on an overall breadth of 20 cm. Toward the southern part of this layer the rings became smaller, no more than 50 mm in diameter.

The schists to the south still contain carbon sacs in an area of 1 m breadth, nearest to the main layer. Here the sacs are small and rounded, no more than 15 mm in diameter. They are scattered over the surface of the rock. The border lines between the metapelitic and metapsammitic beds cannot be determined either here

or in the other layers at Tähtinen. The sacs are usually found in irregular patches of metapelite included in metapsammite.

All *Corycium* samples collected by the author were inclosed in a fine-grained, dark-gray phyllite, blackish on the weathered surface. Small biotite flakes were seen on fresh surfaces. Under the polarizing microscope, a thin section of a rock specimen collected at Tähtinen (sample No. 7) was found to consist mainly of quartz, plagioclase, biotite, and disseminated carbon. Apatite and epidote were present as rare accessories. Sericite was found as an alteration product of plagioclase and as small scales inside some quartz grains. Some biotite was altered to chlorite. The oblong subangular quartz grains which measured up to 0.6 mm in diameter were usually devoid of undulatory extinction. The plagioclase (ca. An_{30}) grains measured up to 0.4 mm; they were sericitized and often filled up with finely disseminated carbon. Biotite occurred as small brown flakes and their accumulations, with distinct subparallel arrangement. Carbon was evenly, though thinly, disseminated throughout the thin section, often as subparallel bands which determine the orientation of the rock. The phyllite is blastoclastic with fairly well developed schistosity.

Three *Corycium* samples (1, 6, 13), collected some 200 m southeast of Tähtinen, were investigated. One of the sacs (No. 1) was elliptical, with diameters of 10 and 25 mm, while the other two were nearly circular, 11 and 12 mm in diameter. The first one was near the contact between the metapelitic and metapsammitic layers. The metapelitic layer consists of small grains of quartz, plagioclase, and biotite, with accessory muscovite, finely disseminated carbon, and apatite. The grains measured from less than 0.01 to 0.07 mm, or a little more. The layer is recrystallized and has a lepidoblastic texture. The micas show a distinct subparallel arrangement; their flakes lie parallel to the contact line. The contact zone between the two layers occasionally contains much biotite. The mica seam is 0.7 mm thick.

The metapsammitic layer is quite similar in composition and texture to the phyllite. The plagioclase grains measure up to 1.4 mm; the mineral is altered into sericite and epidote. In addition to the minerals listed above as accessories, a few grains of epidote and tourmaline have been found in this specimen. The amount of carbonaceous matter is quite low but increases 4 to 6 mm from the border of the *Corycium* circle, and a dark circle is present around the *Corycium*, best seen on weathered or polished rock surfaces.

The *Corycium* proper in the specimen described is composed of a layer of very finely divided black carbonaceous matter a little less than 1 mm thick. The darkest portions of the circle contain carbon in the form of homogeneous opaque substance. On the inner and outer contacts the amount of carbon decreases quite sharply; it is here usually found as rims around the different minerals, or proceeding inside the plagioclase grains along the cleavages. Mineral grains are always imbedded in the carbonaceous rim which thus acts as a cement. Quartz and sericitized plagioclase are present as clastic grains, and biotite occurs in a subordinate amount. Chlorite—as an alteration product of biotite—apatite, and epidote occur as accessories.

The rock inside the carbon circle differs from the coarser-grained layer of phyllite only by its greater content of finely disseminated carbon.

The remaining two *Corycium* specimens are quite similar to that described above.

Plagioclase grains (An_{5-10} and An_{30-35}) are present in the surrounding metapsammitic rock. A few grains of zircon and a little hematite are found among the accessory minerals. The carbonaceous matter is concentrated, also in these samples, into a 4- to 6-mm shell surrounding the *Corycium* proper. Inside the *Corycium* the amount of carbon decreases toward the center of the ring. At the *Corycium* contact the biotite inside the rim is often chloritized, and hematite pigment is present.

Some 20 meters southeast of the pier at Alanen the author, in the summer of 1946, found still another type of the carbon sacs (Pl. 4, figs. 3, 4). Here, in a metapsammitic layer, rounded, a little elongated, or irregularly elliptical thin (1 mm) black rings usually contain a tiny black carbon-rich remnant at their center. The rings measure 10 to 35 mm in diameter; the inclusion is only 6 to 13 mm long and from less than 1 mm to 3 mm wide. The zone around the remnant is bleached; the inner zone is darker than the surrounding schist.

Another variety of inclusions (No. 5) was collected near the villa Rapakivi (Saarinen) at Alanen, about 1 km southeast of Tähtinen (Pl. 3, figs. 3, 4). The classical *Corycium* forms are evidently restricted to the northeast parts of the peninsula. The sacs found elsewhere are more obscure. An oblong somewhat twisted sac 43 by 6 to 8 mm was seen on the rock surface. The weathered carbon ring was 1 to 2 mm wide. In thin section, the carbonaceous layer, 2 to 6 mm wide, was found to be twisted and plicated due to miniature folding and faulting. A fragment of metapelitic phyllite was found inside the carbon ring, and the whole was intersected by later tiny quartz stringers. The contact between the phyllite fragment and the surrounding metapsammite was sharply defined. The presence of epidote in small grains and of limonite in the carbon-rich zone may be traced to the effects of later mineralization.

The origin of *Corycium* has been discussed by Sederholm, at some length, on several occasions (1897, p. 91–3; 1911, p. 27–8; 1912, p. 517–18; 1924, p. 717–18; 1925a, p. 360). He rejected the interpretation of the carbon sacs as concretions surrounded by a later coating of carbonaceous matter, pointedly citing the homogeneity of the clastic sedimentary matter both inside and outside the carbon rims. A suggestion anent the deposition of the carbonaceous matter along cracks present in the phyllites is similarly rejected, with special reference to the existence of tiny carbon streaks in the phyllite, presumably formed as fine detritus of primarily present compact masses. Therefore, he assumed that the carbon sacs must have existed as such in the sandy silts prior to the consolidation and metamorphic processes, and, unable to interpret the sacs as of inorganic origin, finally suggested that they are remains of organisms. Since the fluctuations in size seem to exclude an animal origin, it is decided that they are vegetal remains, most likely of primitive algae.

The secondary origin for *Corycium* as suggested by Krejci-Graf (Krejci, 1924) was most vigorously opposed by Sederholm. The single case of *Corycium* occurring on the contact between metapsammitic and metapelitic layers (Fig. 2), earlier presented by him as the only one suggesting a secondary origin, is further elucidated. Sederholm once more explicitly stated that the sacs existed already during the deposition of the sandy layer and thus were filled out with sand, in some rare cases with silt and clay; the carbonaceous substance formed the matrix between the clastic grains in the present-day phyllite.

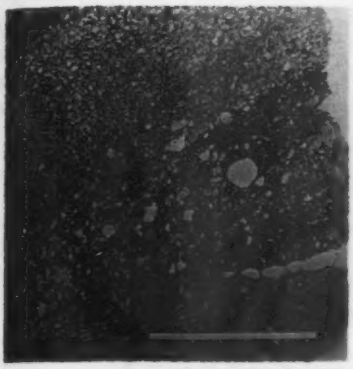

FIGURE 1. *Corycium* (1)
Tähtinen, Aitolahti. Thin section. No nicols.
Length of scale 10 mm. Photo: K. R.

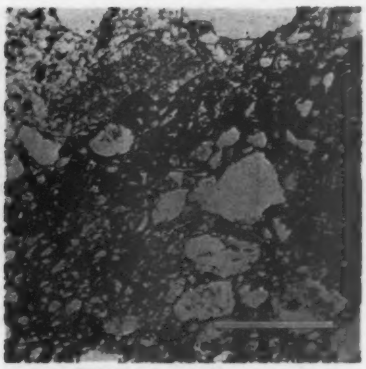

FIGURE 2. *Corycium* (1)
Tähtinen, Aitolahti. Thin section. 1 nicol.
Note the feldspar grain with carbon inclusions at the contact. Length of scale 1 mm.
Photo: K. R.

FIGURE 3. INCLUSION (5) IN PHYLLITE
Near Saarinen at Alanen, Aitolahti. Length of scale 10 mm.
Photo: K. R.

FIGURE 4. INCLUSION (5) IN PHYLLITE
Thin section. No nicols. Length of scale 10 mm. Photo: K. R.

CORYCIUM IN THIN SECTION. CARBONACEOUS INCLUSION

FIGURE 1. CARBON-BEARING SLATE FRAGMENT IN PHYLLITE
Toivola nr. Alanen, Aitolahti. Length of scale 20 mm. Photo: K. R.

FIGURE 2. CARBON-RICH SLATE FRAGMENT IN PHYLLITE
Alanen, Aitolahti. Length of scale 20 mm. Photo: K. R.

FIGURE 3. CARBON SACS WITH CARBON-RICH REMNANTS
Alanen, Aitolahti. Length of scale 10 mm.
Photo: K. R.

FIGURE 4. IRREGULARLY SHAPED CARBON SACS WITH CARBON-RICH REMNANTS
Alanen, Aitolahti. Length of scale 10 mm.
Photo: K. R.

CARBON-BEARING SLATE FRAGMENTS. CARBON SACS WITH CARBON-RICH REMNANTS

Special attention must be paid to a recent paper on the mode of preservation of plant fossils (Kryshtofovich, 1944) which contains important new aspects of the matter. The new concept of phytoleims, or mummified plants, is defined by Kryshtofovich, (1944, p. 60, 61) as pertaining to all plant fossils in which the original tissue or plant organ, whether a carbohydrate or even shell, as in the case of, *e.g.*, diatoms,

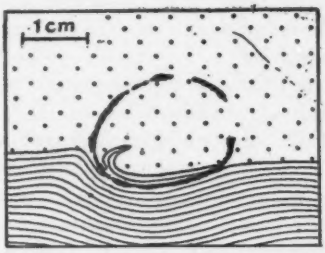

FIGURE 2.—Corycium *on the contact between metapsammitic and metapelitic layers*

is preserved with only slight alteration or transformation of the original material, but without any posthumous mineralization or petrification, *i.e.*, exchange for mineral matter. Such phytoleims are commonly found as residua with only the most resistant parts preserved. They are formed when the original carbohydrates, related materials, and their derivatives are, partly or entirely, altered into hydrocarbon, or rarely into carbon.

Kryshtofovich further stated (1944, p. 68) that when a massive plant object with a cavity easily accessible for penetration by mud and sand is embedded in a muddy sediment either during life or *post mortem*, it will become filled with the sediment, and after diagenetic and metamorphic processes the filling (core) will not differ in its color from the surrounding rock. Still more important, when the matrix and the core are solidified, the object itself may degenerate into an insignificant coaly remnant.

The above statements may be applied to cover the history of our Archean carbon sacs, if the matter is considered from a purely paleontological point of view, and they are of organic origin. Kryshtofovich's discussion evidently further supports the concept of *Corycium* as an algal remain, as presented and passionately defended by Sederholm.

Sederholm was also aware of a certain objection to the organic origin of the carbon sacs, *viz.* their weak stretching and shearing in spite of their present vertical position. However, since neither the small slate fragments encompassed by the phyllite nor the pebbles and cobbles of the conglomerates of the Tampere area are highly deformed, he considered the point to be of no decisive importance. Due to the general lack of a large-scale deformation of the phyllite formation, the *Corycium* sacs have been preserved through eons of geological history.

In search of *Corycium*-like inclusions in slates and shales elsewhere, the peculiar protrusions described by Von Eckermann (1936, p. 237–238) from the pre-Jotnian slates of the Upper Loos sedimentary series in the Loos-Hamra Region, Orsa Finnmark, Sweden, must be considered. In the gray, strongly pressed slates at the Ryggskog quarries, oval nodular protrusions are found on the planes of sedimentation,

varying from 4 to 10 cm in length, and having a concretionlike appearance. No concentration of authigenic material is distinguished under the microscope, and the protrusions are described simply as small areas where the otherwise continuous sedimentation is discontinued. The surface is always convex, and to it is attached a minute quantity of grayish-brown powder. Von Eckermann suggests that they are remains of gas bubbles developed in the slime and compressed by the weight of the overlying sediment layers, although the *Corycium* and its interpretation by Sederholm must not be forgotten.

CARBON-BEARING SLATE FRAGMENTS: Glossy dark-gray slate fragments very rich in carbon are common in the phyllites (Pl. 4, figs. 1, 2). They are usually elongated lenticular or ellipsoidal bodies or irregularly shaped inclusions, varying in their length from less than 1 cm to several tens of cm. Their contact with the surrounding phyllite which is either metapsammitic or metapelitic is always sharp. More irregular angular bodies are also met. Often, due to their hardness, the inclusions protrude a couple of mm over the phyllite surface. The fragments are most plentiful along the coast south of Tähtinen. Similar forms were discovered, in the summer of 1945, on the opposite shore of Lake Näsijärvi, in bedrock approximately 1 km southeast of Valkeekivi, parish of Yöljärvi, during the detailed mapping of the phyllite belt carried out for the Geological Survey of Finland by Mr. Ahti Simonen, State Geologist. Another occurrence was found by Mr. K. J. Neuvonen on a small island, Keisaari, about 3 km southeast of the former occurrence.

A thin section of a sample (No. 4) collected near the pier at Alanen was mainly composed of a very finely divided matrix of carbon powder showing marked variations in amount in its parallel layers. The other main constituents were recrystallized quartz and biotite. Muscovite and apatite were present in subordinate amounts. The maximum grain size was measured as 0.03 mm. The contact between the inclusions and the surrounding normal metapsammitic sediment was sharp. A little carbonaceous matter was found in the latter near the contact.

According to its mode of occurrence as the matrix intimately mixed with the original constituents of the slate fragments, the carbonaceous matter may well be considered as a primary constituent of the clays now occurring in the form of slate, and for reasons given below an organic origin may be attributed to it.

CARBON-BEARING CALCAREOUS INCLUSIONS IN THE PHYLLITE: Lenticular or rounded carbon-bearing bodies were first discovered by Sederholm in 1908 in the phyllite on a little rock in the lake southwest of Ajonokka (Tähtinen) (Pl. 5). Similar forms are found on the shore south of Tähtinen. They are considerably larger than the carbon-bearing schist fragments or the *Corycium* proper, the maximum length measured being 55 cm. Concentric layers of different carbon content may be encountered. Sederholm felt inclined to consider them organic remains but was unable to secure convincing proof.

Often the material included is weathered away, and merely lenticular cavities are present on the phyllite surfaces, their maximum length being measured as 60 cm, width 5 to 20 cm, and the depth of the larger cavities up to 20 cm (Pl. 6, fig. 1).

Near the pier at Alanen a train of these bodies of varying sizes can be investigated in more detail. Here on the rock surface the inclusions are rounded, somewhat

FIGURE 1. ROUNDED CARBON-BEARING BODIES IN PHYLLITE
Submerged rock in Lake Näsijärvi, S. W. of Tahtinen, Aitolahti. Length of scale 50 mm. Photo: J. J. Sederholm, 1908.
(Geological Survey of Finland, No. 2201).

CARBON-BEARING BODIES IN PHYLLITE

FIGURE 1. WEATHERED CARBON-BEARING CALCAREOUS INCLUSIONS IN PHYLLITE
Tähtinen, Aitolahti. Photo: K. R.

FIGURE 2. LENTICULAR AND ROUNDED CARBON-BEARING CALCAREOUS INCLUSIONS IN PHYLLITE
Alanen, Aitolahti. Photo: K. R.

CARBON-BEARING CALCAREOUS INCLUSIONS IN PHYLLITE

elongated or elliptical, their largest diameter ranging from 3.5 to 50 cm (Pl. 6, fig. 2). Megascopically, they contain small quartz and feldspar grains on the weathered surface and are similar to the surrounding metapsammitic sediment save for their darker color. The largest grains in both measure 1 mm or a little more. The inclusions, being softer than the rock surrounding them, sink on a weathered surface a few mm under the surface of the metapsammitic sediment. No carbon is distinguished in the inclusions with the unaided eye.

Under the microscope a remarkable content of carbonate (chemically proved to be calcite) is at once established; in the weathered part of the inclusions, this mineral has been dissolved completely. The other main constituents are quartz in slightly elongated clastic grains and recrystallized aggregates, recrystallized biotite flakes, their trains and accumulations, highly sericitized plagioclase (An_{25-30}), and finely disseminated carbon. The carbon content, however, is much smaller than indicated by the dark color of the inclusions on the weathered surface. Minor constituents are chlorite as an alteration product of biotite, a few grains of epidote, sphene, apatite, limonite, and recrystallized muscovite scales. The matrix consists of recrystallized quartz and biotite, with calcite, limonite, and carbon. Biotite shows a distinct subparallel arrangement. The texture of the rock is blastoclastic, and, save for the quartz grains which already are partially corroded at their borders, the rock is considerably altered and recrystallized.

The calcite content of these inclusions explains readily their easy disintegration. Their origin might reasonably be similar to that of the calcareous concretions in the Archean varved schists explained by Eskola (1932, p. 19–24) to be like the calcareous concretions in the Pleistocene varved clays. In the present case the mineral assemblage represents metamorphism at a quite low temperature.

GRAPHITE FROM MÄNTYHARJU

A sample of graphite from the graphite mine at Kärpälä in the parish of Mäntyharju was included in the material chosen for the present investigation. According to Laitakari (1925, p. 28), this occurrence is the biggest one found in Finland and forms a lenticular body surrounded by gneiss. The graphite body consists mostly of fine-grained or compact masses, but graphite scales are common. Laitakari (1925, p. 78–85) suggested a sedimentary origin for the graphite layers and bodies included in the crystalline schists of primarily sedimentary character, the primordial carbonaceous material being of organic origin. That sediments may contain carbon also in the form of graphite has been shown by the observation of Sauramo (1938) that small amounts of this material are present in late-Glacial silts of Finland. The amount of graphite recorded by Sauramo in a silt from Leppäkoski is 0.0015 per cent.

White stated earlier (1908, p. 298) that the discovery of gelatinous micro-algae as constituents of hydrocarbon-bearing strata in Ordovician and younger rocks might strongly suggest an algal origin for the still older graphites interbedded in metamorphic sediments of the Laurentian or Algonkian.

The Mäntyharju graphite deposit belongs to the eastern border zone of the Katarchean Sveco-Fennian formations.

GRAPHITE PHYLLITE FROM KEMI

In the North-Bothnian Downfold area graphite phyllites are met with which, according to Hausen (1936, p. 27) consist of quartz, biotite, and streaks of graphite. A sample of such phyllite, containing also minute lenticular augen of pyrite, from Kalkkimaa near Kemi was included in the present investigation. These phyllites belong (Hausen, 1936, p. 70) to the Karelidic cycle of sedimentation (Sederholm's cycle III), and the sedimentary organic origin of the carbon, as in other graphite-bearing schists of the Finnish pre-Cambrian, is now generally accepted by Finnish geologists.

CARBON-BEARING SCHIST FROM PALTAMO

In the eastern part of the Karelidic zone of East Finland occur graphite- and sulfide-bearing Kalevian phyllites over comparatively large areas. According to Wilkman (1931, p. 187–188) the schists of the Kajaani area are very fine-grained or nearly aphanitic dark-gray rocks, usually distinctly bedded. They are composed of very small rounded quartz grains, muscovite and biotite flakes in subparallel arrangement to the schistosity, and small grains or stringers of pyrite and pyrrhotite. In the carbon-bearing schists the carbonaceous particles are concentrated in fine strips parallel to the schistosity, alternating with streaks richer in quartz.

A specimen of this phyllite found at Paakki in the parish of Paltamo, was selected for the present purpose.

SHUNGITE FROM SHUNGA, KARELO-FINNISH S.S.R.

A most remarkable deposit of coaly matter is at Shunga (Finnish: Sunku) on the Zaonezhye Peninsula (Finnish: Äänisniemi) in the Karelo-Finnish Soviet Socialist Republic. The discovery of the first indications of carbonaceous matter dates as far back as 1842 (Komarov) and 1860 (Helmersen), according to Sudovikov (1937, p. 50). The Zaonezhye Peninsula is composed of Jatulian formations belonging to the Karelidic (III) cycle of Sederholm's classification. The carbonaceous matter is found intercalated in dolomitic limestones, and four varieties differing in appearance and carbon content are distinguished by the Russian geologists. According to Sudovikov (1937, p. 51–57) the first is the most interesting though less widely distributed. It is characterized by jet-black color, adamantine luster, conchoidal fracture, and high carbon content (max. 98.77%). Very interesting is the relatively high content of several trace elements in its ashes, *e.g.*, Ti, V, Mo, Cu, Ni, Zr, and Ba. These elements, however, are probably due to the metasomatism produced by near-by diabase intrusions. X-ray examination has revealed the presence of graphite in the first variety; the others were noncrystalline.

All of the shungite varieties have been interpreted as bituminous coals similar, according to Timofeev, to anthraxolite. The first and purest variety probably has been produced by action of diabase magma upon the black carbon-bearing pelitic slates, but according to Eskola (personal communication), this variety may be regarded as a "carbonized" hydrocarbon.

A sample of the first variety of shungite from Shunga was included in the material for the present investigation.

Shungitic rocks have also been encountered elsewhere in the Jatulian terranes of East Fennoscandia. Shungitic shales occur at Veljakanjoki in Soanlahti, and in Suojärvi shungite layers are present in the Jatulian shales. Both of these occurrences now lie on the Russian side of the boundary line. The Suojärvi shungite as described by Metzger (1924) confirms the organic origin of the shungite, affirmed by Inostranzev in 1880. According to Metzger (1924, p. 62–64), the shungite is a real anthracitic coal measure, though small and of inferior quality, originally deposited as a sapropelic layer in the mudstone. Metzger also pointed out the role of shungite as a transitory member to graphite, while Frauenfelder (1924, p. 43) placed it definitively into the latter category.

ORIGIN OF CARBON IN METAMORPHOSED ARGILLACEOUS SEDIMENTS OF THE PRE-CAMBRIAN

As pointed out, the Finnish geologists believe that the carbon present in these schists is of organic origin. For instance, Laitakari (1925, p. 73, 76) interpreted the graphite and the sulfides as primary constituents of bituminous or sapropelic shales and slates and compared these schists with geologically younger alum shales and bituminous sediments. In addition, Eskola (1932, p. 27–28) stated explicitly that the presence of primary sedimentary structures observed at all stages of metamorphism affords proof that "the carbon-bearing schists also comprise bituminous shales formed in the same way as recent bituminous muds in deep closed basins in which hydrogen sulphide results from the decay of organic substances in the absence of oxygen."

In the Karelide zone of East Finland a transition series of metamorphosed argillaceous sediments ranges from the Jatulian shales to the recrystallized mica schists and partly granitized gneisses. The graphite-rich members of this series are nearly always relatively fine-grained (Eskola, 1927, p. 70). This, Eskola explained, is because the finely divided carbonaceous matter bars the growth of the mica flakes. According to Eskola, there is no difference in the degree of metamorphism between the carbon-bearing slates and the coarser-grained carbon-free mica schists.

This peculiar fact is further elucidated by the results obtained by Väyrynen (1927, p. 93–94) when investigating certain carbon- and sulfide-bearing phyllites of the Karelide zone. He established the presence of extremely finely divided graphite matrix in a phyllite from Puolanka with a carbon content as high as 15.72 per cent and found the dissemination comparable with a solid solution. Hence, he decided that the carbonaceous matter evidently was a primary constituent of the original sediment and had not been introduced later. The primary nature of the carbon also added to the possibilities of introducing a similar origin for the sulfides as well (Väyrynen, 1927, p. 97) and was, further, considered proof of the presence of organic life during the deposition of these sediments, as Väyrynen later stated (see Wegmann et Kranck, 1933, p. 20–21).

According to Eskola (1932, p. 27) the carbon-bearing schists have originally been subaquatic sediments, and organic life has existed in the waters in which they were deposited.

Pyrite and pyrrhotite occur in the carbon-bearing schists almost invariably, irre-

spective of the degree of their metamorphism. Such regional disseminations in the schists, according to Hausen (1943, p. 17–19), are evidently of sedimentary origin and co-ordinate with those occurring in the alum shales of sapropelic origin. Also Pettijohn (1943, p. 945–949) attributed an organic marine origin to the pyrite- and carbon-bearing graywackes and their associated slates of the Canadian Shield.

To sum up what has been said above, we may trace, by geological reasons, a common organic origin for the carbon- and sulfide-bearing slates and schists of the pre-Cambrian of Finland with actual argillaceous composition and primary sedimentary structures. A transition series is present from the fine-grained Jatulian shales to the mica schists and partly granitized paragneisses on the one hand, and from the slightly metamorphosed anthracitelike shungite to the layers and bodies of crystalline graphite embedded in highly crystalline mica schists and paragneisses on the other. The high degree of similarity of the graphite- and sulfide-bearing slates with the alum shales of Paleozoic and later age strongly suggests an identical origin. However, the final proof is still lacking, and the organic origin is deduced solely by the use of the uniformitarian principle.

ENRICHMENT PROCEDURE FOR CARBON

Since the carbon, in the case of the *Corycium* proper, was present as a finely disseminated matrix between the quartz and feldspar grains, it was pre-enriched prior to the combustion. Two principally different methods were applied in order to obtain a concentrate: flotation and treatment with hydrofluoric acid. Finely powdered samples of the *Corycium* sac with the carbon-rich kernel were used for the concentration.

FLOTATION: More than 40 experiments were needed to obtain satisfactory results in the separation of the graphite from the other minerals in the samples. A number of compounds were tried as frothers and depressants. In the final procedure 0.2 to 0.7 g of the material were placed into a globe-shaped separatory funnel with a capacity of 100 ml (Fig. 3) which was connected with a filtering flask and contained 50 ml distilled water. Three drops of kerosene or 0.1 per cent pine oil were added as a frother, and a steady current of air was passed through the solution by means of a vacuum connection. The sludge was collected in the filtering flask, and the graphite froth was rinsed with ethanol into a small beaker where it was purified by decanting several times with ethanol, washed with ethyl ether, and dried in a drying cabinet at 200°C. for 2 hours. The samples were floated at least twice, and the concentrates obtained were re-treated to ensure a maximum amount of pure graphite.

Under the microscope the final graphite concentrates proved to be approximately 90 per cent pure; the rest consists of quartz and feldspar with minor amounts of biotite. The amount of recovered graphite was usually found to be about 10 per cent of the amount of the rock powder originally used for the enrichment.

In the mass spectrometric determination of the carbon, contamination by the organic reagents used in the different stages of the work seems a possible source of error, but, as the amount of the flotation reagents is quite small, it must be considered that all traces of them have been removed by the washing with alcohol and ether which, in turn, escaped during the drying. The graphite preparations obtained are thus considered free from contaminating carbon compounds.

TREATMENT WITH HYDROFLUORIC ACID: This consists of the decomposition of the finely powdered sample (approx. 0.5 g) with strong (40%) hydrofluoric acid in a platinum basin whereby the carbon is concentrated in the insoluble residue. To prevent deposition of silica due to the hydrolysis of SiF_4, a small amount of concen-

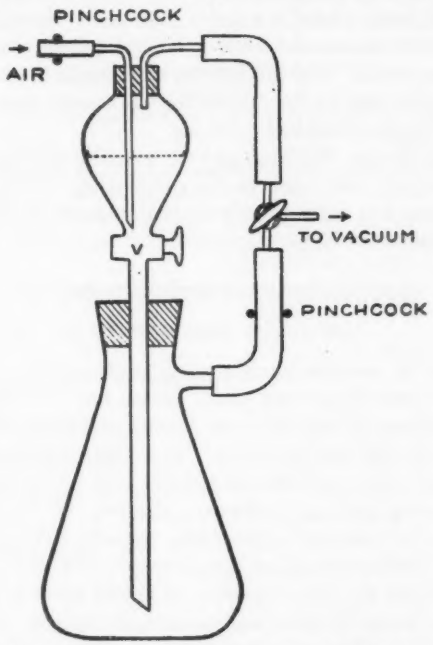

FIGURE 3.—*Apparatus used for the separation of graphite by flotation*

trated sulfuric acid, ranging from 2 to 4 ml, was added to the hydrofluoric acid. The samples were treated with successive portions (5 to 10 ml) of H_2F_2 on a water bath, and the residues were heated on a sand bath until SO_3 fumes were expelled. The soluble salts were washed away by repeatedly adding small amounts of distilled water, occasionally acidified with a few drops of strong hydrochloric acid. After drying for 2 hours at 200°C. the purity of the graphite obtained was investigated under the microscope. Less than 10 per cent of silicate grains were found to be present. The recovered graphite amounted to approximately 10 per cent of the original weight of the samples. As to their content of irrelevant carbonaceous compounds, the graphite samples were considered safe enough.

COMBUSTION OF CARBON

One of the central problems of this investigation was the development of a suitable combustion method and apparatus for converting the carbon dioxide into barium carbonate without the addition of any carbon compounds from extraneous sources during the different stages of the combustion. A special absorption apparatus was

finally constructed to meet the case. A description of the apparatus and of the details of the method of combustion will be published elsewhere. The graphite samples were burned in a stream of purified oxygen. The carbon dioxide was collected in saturated barium hydroxide solution where barium carbonate was precipitated. The precipitate was filtered off and washed with CO_2-free water in the absorption assembly, dried, and finally stored in a sealed glass tube. Special precautions were observed to ensure the barium carbonate precipitates from contamination by extraneous carbon compounds. The precipitates are thought to be very pure.

The amount of carbon used for the combustion was usually approximately 200 mg. The recovered $BaCO_3$ amounted to 50–300 mg.

The graphite from Ersby, Parainen, and the graphite phyllite from Kemi were treated with hydrochloric acid prior to the combustion to remove any carbonate impurity. The carbon was enriched only in the *Corycium* samples and the carbon-bearing slate fragments from Ylöjärvi.

SPECTROCHEMICAL DETERMINATIONS

SPECTROGRAPHIC TECHNIQUE

VANADIUM: Since the samples consisted mainly of carbon, a mixture of 90 per cent graphite powder with 10 per cent quartz was used as a base bearing in mind the observation of Kvalheim (1941) that the intensities of the V lines are strongly affected by changes in the base substance. The carbon samples and the standard mixtures were diluted with 2 parts of a mixture of 50% NaCl, 45% quartz, and 5% Cr_2O_3, chromium being used as a reference element. The determinations were carried out by means of a method presented by the author (Rankama and Joensuu, 1946) using a Zeiss Three-Prism Glass Spectrograph. The V I line 4384.722 Å was measured which allowed the V_2O_5 content to be traced down to 0.001%. The line Cr I 4545.956 Å was chosen for safety and correction purposes. High-purity carbon electrodes were used (*cf.* Rankama and Joensuu, 1946, p. 12), the depth of the cathode bore being increased to 6 mm to enhance the sensitivity. After a 4-minute exposure the samples were completely consumed. The spectra were photographed on Kodak IV-F plates.

The standard length of the safety Cr line was determined as an average from 15 exposures. If there was a deviation in the length of the safety line from its standard length, a correction factor was used for the V line. This time, however, the difference between the measured and the normal length was used instead of the length ratio. The result was considered more accurate, for reasons which cannot be entered here.

When analyzing the carbon-bearing schists a comparison series with quartz base was used, diluted with the $NaCl—SiO_2—Cr_2O_3$ mixture as given above. It was found that the change in the base substance affected the V line more than the Cr line.

COPPER AND MOLYBDENUM: These elements were determined with the Zeiss Quartz Spectrograph Qu 24. The width of the spectrograph slit was 0.004 mm, and it was evenly illuminated by means of three lenses. Agfa spektral blau extra hart plates were used and the time of exposure was 2 min. 30 sec. The dimensions of the cathode bore were: diameter, 1.5 mm; depth, 2.5 mm. The Cu I lines 3247.540 Å

and 3273.962 Å, and the Mo line 3170.347 Å were used for the identification of these elements, their amounts being estimated visually by means of a Gatterer projection comparator. Another series of the spectra was photographed from mixtures diluted with one part NaCl, in a cathode bore of only 1.5 mm depth, in order to reduce the blackening of the background. Now the time of exposure was 1 min. 30 sec.

TABLE 1.—*Copper, vanadium, and molybdenum in carbonaceous pre-Cambrian materials from East Fennoscandia*

In per cent

Sample	Enrichment procedure	CuO	V_2O_5	MoO_3
Carbon from *Corycium* (1). Tähtinen, Aitolahti	Flotation	0.004	0.011	0
Carbon from *Corycium* (1). Tähtinen, Aitolahti	H_2F_2	0.005	0.005	n.d.
Carbon from *Corycium*-like inclusion (5). Saarinen, Aitolahti	Flotation	0.015	0.006	0.02
Carbon from *Corycium*-like inclusion (5). Saarinen, Aitolahti	H_2F_2	0.02	0.001	0.01
Carbon from slate fragment (19). Nr. Valkeekivi, Ylöjärvi	Flotation	0.01	0.004	0.015
Carbon from slate fragment (19). Nr. Valkeekivi, Ylöjärvi	H_2F_2	0.01	0.004	0.01
Phyllite (7). Tähtinen, Aitolahti	—	0.001	0.015	0.001
Graphite (S.M. 4985). Ersby, Parainen	—	<0.001	~0.001	0
Graphite (S.M. 6515). Kärpälä, Mäntyharju	—	~0.1	0.12	0.01
Graphite from graphite phyllite (G.F. 9797). Kalkkimaa, Kemi	—	~0.1	0.04	0
Graphite from carbon-bearing schist (G.F. 2239). Paakki, Paltamo	—	~0.1	0.04	0
Shungite, 1st variety. Shunga, K.F.S.S.R.	—	0.003	0.12	0.01

RESULTS

The results of the spectrochemical determinations are presented in Table 1.

The Parainen graphite and that from the phyllite at Kalkkimaa were treated with hydrochloric acid prior to the analysis in order to remove the carbonate matter.

The H_2F_2 treatment has in many cases dissolved a considerable part of the cations present in the carbon (Table 1). When the spectra of the flotation and hydrofluoric acid concentrates were compared, the latter often displayed weaker lines than the former, this rule being valid for all elements present in the spectra of the concentrates.

DISCUSSION OF RESULTS

It is well known that, among many other elements, copper, vanadium, and molybdenum are concentrated in Nature through organic processes. Copper is essential to the growth of plants, and the copper-bearing haemocyanin plays the role of hemoglobin in molluscan and crustaceous blood. Molybdenum is in some cases enriched in matter of vegetal and animal origin. High concentrations of vanadium occur in some plants and in the blood of certain marine organisms, *e.g.*, *Ascidiacea*. The

enrichment of vanadium in coals is still another remarkable instance of its presence in organic Nature. According to Leutwein (1941, p. 81) it is highly probable that especially the lower forms of living organisms under certain circumstances, like oxygen deficiency, may use vanadium for their sustenance.

All animals rich in vanadium prefer slime as a dwelling place (Berg, 1936, p. 17), and this may apply to those rich in copper as well. Since such animals belong to the lower ranges of the Animal Kingdom, it might be reasonable to try to use these elements in elucidating the origin of the carbonaceous matter in the pre-Cambrian.

Table 1 shows that the copper and molybdenum contents of the *Corycium* and associated carbons are higher than in the surrounding phyllite. As to vanadium, the case is just the reverse.

As pointed out by Berg (1936, p. 16), the copper content of sediments is usually a result of concentration in and deposition from the weathering solutions circulating in the sediments. Since the high copper content in water can be traced to previous copper-bearing sediments, the occurrence of copper-rich organisms in such cases is the effect and not the cause of the copper-bearing habitat, and the later concentration of this element is no real organogenic phenomenon. With due consideration to the possibility of the inorganic origin of the concentrations of Cu, V, and Mo we may, nevertheless, be free to interpret the carbonaceous accumulations in the phyllites of the Tampere Belt as being of organic origin, since the phyllite contains less copper and molybdenum than *Corycium* and the carbon-rich fragments.

In the other pre-Cambrian carbons, the analyses (Table 1) show rather high content of copper in the graphite-bearing schists and in the Mäntyharju graphite, while the content in shungite is quite low and in the Parainen graphite negligible. The vanadium content partly follows the above rule; molybdenum is present only in shungite and in the Mäntyharju graphite. The graphite from Parainen differs from all other samples in its low content of all of the elements investigated.

The high copper content of the three samples might be due to contaminating sulfides and is thus no clue to the origin of the carbon. On the other hand, the vanadium content in the graphite-bearing schists seems to be comparable to some of those in the Swedish alum shales: the *Paradoxides* and *Olenus* shales of Skåne, Östergötland, and Öland, which according to Westergård (1944a, p. 15; 1944b, p. 8, 17) contain 0.01 to 0.26 per cent V. The values reported by Assarsson (1941, p. 182) on V, Mo, and W in the alum shales of Närke, Kinnekulle, and Östergötland in Sweden range from 0.02 to 0.20 per cent V, 0.008–0.03 per cent Mo, and from zero to some hundredths of a per cent for W. However, Assarsson expressly pointed out that no relationship exists between these contents and that of organic material and suggested that V, Mo, and possibly also W must be bound to sulfur in the shales. In any case, an organic origin of the present material similar to that of the alum shales is not excluded since all sapropelic sediments are rich in vanadium.

A number of minor elements is known to be present in the shungite. According to Sudovikov (1937, p. 54) the amount of MoO_3 in the first variety may be as high as about 0.005 per cent, while V_2O_5 is present, and CuO varies from zero to 0.0005 per cent. Sudovikov also stated (1937, p. 55) that many of the trace elements in shungite may be accounted for by the contamination by intrusions of diabase magma.

According to Eskola, the first variety of shungite is produced by "carbonization" of hydrocarbons.

Lokka's (1943) vanadium determinations of pre-Cambrian materials of East Fennoscandia corroborate the observation of Assarsson (1941) that vanadium does not follow carbon. Lokka (1943, p. 68) suggested that the former element might be enriched by secondary processes. He gives the value of 0.132 per cent V_2O_5 for the graphite from Kärpälä, Mäntyharju, and 0.016–0.160 per cent in the first variety of shungite (according to Russian authorities). These values agree quite well with the figures given in Table 1. Of high interest is the carbonaceous schist of Tahravaara in Tulemajärvi, K.F.S.S.R., analyzed by Lokka and showing a very high content of carbon, about 37 per cent. As far as known to the author, this is the highest carbon content ever recorded in a pre-Cambrian schist.

The results of spectrochemical analysis seem to furnish some evidence, although not conclusive, that the carbon present in the *Corycium* and in the graphite-bearing schists investigated originated by organic processes. The graphite from Parainen seems to be of inorganic origin. It is of interest to note that Leutwein (1941, p. 83) gave for three paragneisses vanadium percentages ranging from 0.002 to 0.007 per cent V, while his average for orthogneisses is $\leqq$0.0005 per cent V. He was thus able to use the V content as a criterion of the origin of the gneisses.

MASS SPECTROMETRIC DETERMINATIONS

MASS SPECTROMETRIC TECHNIQUE

The barium carbonate precipitates obtained from the different carbon-bearing materials included in this study were submitted to mass spectrometric assay. The determinations were carried out in May 1947 by Professor Alfred O. C. Nier at the Department of Physics, University of Minnesota, with his new 60-degree mass spectrometer.

The samples were converted to carbon dioxide, and the C^{12}/C^{13} ratio was determined from the relative heights of the mass 44 and mass 45 peaks, the answers being corrected for the $C^{12}O^{16}O^{17}$ contribution to the mass 45 peak. In making this correction the O^{17}/O^{16} ratio was assumed to be 1/2500.

A control sample was included in the series of analyses. The samples were analyzed two or three times under as nearly identical conditions as was possible. All of the absolute values may be too high or too low by as much as 2 per cent due to systematic errors in the spectrometer, but as the working conditions were kept nearly identical, the differences in the abundance ratios of the samples should be significant. The average C^{12}/C^{13} ratios should be accurate within about 0.5 per cent.

RESULTS

The results of the mass spectrometric work appear in Table 2.

DISCUSSION OF RESULTS

A number of previous C^{12}/C^{13} determinations are quoted in Table 3. This table is based on results of Nier and Gulbransen (NG) (1939) and West (W) (1945). The

largest number of values is quoted from Murphey (M) (1941), very kindly put at the author's disposal by Dr. Nier. The average values obtained in Murphey's work have been published by Murphey and Nier (1941). As stated by these authors, C^{13} is concentrated in the limestones whereas plant forms prefer the lighter isotope,

TABLE 2.—*C^{12}/C^{13} ratios in carbonaceous pre-Cambrian materials from East Fennoscandia*

No. of sample	Sample	C^{12}/C^{13}			
		Run one	Run two	Run three	Average
1	Carbon from *Corycium*-like inclusion (5). Saarinen, Aitolahti	—	91.6	91.2	91.4
2	Carbon from *Corycium* (1). Tähtinen, Aitolahti	—	92.3	91.6	92.0
3*	Carbon from *Corycium* (6a). Tähtinen, Aitolahti	90.6	91.0	92.3	91.3
4*	Carbon from *Corycium* (6a). Tähtinen, Aitolahti	90.3	90.0	—	90.2
5*	Carbon from slate fragment (19). Nr. Valkeekivi, Ylöjärvi	91.5	91.1	91.2	91.3
6*	Carbon from slate fragment (19). Nr. Valkeekivi, Ylöjärvi	90.6	90.6	90.6	90.6
7	Graphite from graphite phyllite (G.F. 9797). Kalkkimaa, Kemi	90.1	90.8	90.7	90.5
8	Graphite (S.M. 4985). Ersby, Parainen	88.6	88.1	—	88.4
9	Graphite (S.M. 6515). Kärpälä, Mäntyharju	91.7	91.7	91.7	91.7
10	Graphite from carbon-bearing schist (G.F. 2239). Paakki, Paltamo	90.1	89.3	91.6	90.3
11	Shungite, 1st variety. Shunga, K.F.S.S.R.	—	92.9	92.9	92.9

* The sample pairs 3–4 and 5–6 were obtained from the same hand specimen using the different methods described for the enrichment of carbon. Unfortunately, no notes were made concerning the method used in each separate case. Probably, however, 3 and 5 were obtained by hydrofluoric acid.

C^{12}. No age effect was established contrary to the previous statement by Nier and Gulbransen (1939, p. 698) concerning the limestones. West (1945, p. 420) pointed out the systematic differences between the three different series of determinations suggesting that the method of combustion might alter the relative abundances, depending on how diffusion and vaporization operate in the purification of the CO_2, since it would seem to be unlikely that differences between mass spectrometers could have such an effect. It seems to the author, however, that the systematic discriminations in the mass spectrometers might be held responsible for the variations observed, and it is well to remember the warning repeatedly given by Nier that the absolute values of C^{12}/C^{13} may be in error as much as 2 per cent. This would apply also to West's results. On the other hand, West used fractional distillation to separate the hydrocarbons from the oil samples for analysis, and some fractionation of the isotopes might occur during this process. However, as Nier said the differences between the samples should be significant when all samples were studied under nearly identical conditions.

If Table 3 is restudied with the above precautions in mind, the C^{12}/C^{13} ratios are found to be divided into three major groups. Igneous carbon and carbonate carbon have the lowest C^{12}/C^{13} ratios; the carbon of vegetal and animal origin, of bituminous sediments, and of petroleum and natural gas shows the highest values; and the meteorite carbons form an intermediate group. The composition of air clearly depends on the amount of CO_2 produced from the combustion of fuels of organic

TABLE 3.—*C^{12}/C^{13} ratios for various carbonaceous materials*

Sample and location	Age	C^{13}/C^{12}	Reference
CARBON FROM METEORITES			
Cañon Diablo, Ariz.		89.8	M
Cosby's Creek, Tenn.	900± m.y.	89.4	NG
Cosby's Creek, Tenn.		91.6	M
Estherville, Iowa		91.1	M
Homestead, Iowa		91.7	M
Kokomo, Ind.		91.3	M
Finnmarken, Norway		91.3	M
Pavlodar, Siberia, U.S.S.R.		92.0	M
IGNEOUS CARBON			
Diamond. Kimberley, Union of S. Africa	60? m.y.	89.0	NG
Graphite. Ceylon	500+ m.y.	89.8	NG
Graphite. Ceylon		90.2	M
Calcite (with zeolite). Patterson, N. J.		89.9	M
Calcite. Joplin, Mo.		89.4	M
Calcite from nepheline pegmatite. Bancroft, Ont., Canada		89.8	M
CALCIUM CARBONATE AND LIMESTONES			
Clam shell. Boston, Mass.	Recent	88.7	NG
Marine shell		89.5	M
Limestone. Bermuda		89.0	M
Limestone. Teplitz, Bohemia	Upper Cretaceous	89.3	M
Chalk		89.2	M
Limestone. Bavaria	Jurassic	89.2	M
Limestone	Mississippian	89.0	M
Limestone. New Salem, N. Y.	Lower Devonian	89.2	M
Limestone. Champlain Valley, N. Y.	Mid-Ordovician	88.8	M
Limestone. Vermont	Ordovician (380 m.y.)	88.6	NG
Limestone. N. W. Vermont	Upper Cambrian	89.4	M
Limestone Frontenac Co., Canada	Pre-Cambrian	89.3	M
Limestone. Champlain Valley, N. Y.	Pre-Cambrian	89.3	M
Limestone. New York	Grenville	89.3	M
Limestone. New York	Grenville (1200 m.y.)	87.9	NG
AIR AND WATER			
Air. Massachusetts 3/14/38		92.5	NG
Air. Massachusetts 3/22/38		89.9	NG
Air. Minneapolis, Minn. 3/1/41		91.5	M
Sea water		89.3	M

origin (Murphey and Nier, 1941); hence it will not be considered here. The value for sea water checks closely with that for the limestones (Murphey and Nier, 1941). For all other sample groups the ranges are presented in figure 4. The C^{12}/C^{13} range of the samples shows clearly that terrestrial carbons can be divided into two broad groups, inorganic and organic, according to their C^{12}/C^{13} ratios.

TABLE 3—*Concluded*

Sample and location	Age	C^{12}/C^{13}	Reference
BITUMINOUS SEDIMENTS			
Bottom ooze, Mud Lake, Fla.	Recent	91.6	M
Oil shale. Elko, Nev.	Miocene or Pliocene	92.6	M
Kuckersite. Estonia	Ordovician	92.7	M
Kuckersite No. 2. Estonia	Ordovician	92.5	M
Kolm. Gotland, Sweden	Upper Cambrian	92.4	M
Shungite. Shunga, K.F.S.S.R.	Pre-Cambrian	92.7	M
Green River oil shale. Rulison, Colo.		92.5	M
Kerosene shale. Australia		91.7	M
Alum shale (Alaunerde). Germany		92.2	M
PETROLEUM AND NATURAL GAS			
Crude oil. Allen, Okla.		92.8	M
Crude oil. Rusk Co., Tex.		92.3	M
Crude oil. Los Angeles, Calif.		92.0	M
Oil. Emba, U.S.S.R.		92.5	M
Oil. West Texas		91.2	NG
Oil and gas. Barton and Rice Counties, Kan.		94.1	W
Oil. Pottawatomie Co., Okla.		93.2	W
Oil. Winkler Co., Tex.		93.9	W
Oil. Carbon Co., Wyo.		94.1	W
CARBON OF ANIMAL ORIGIN			
Clam flesh. Boston, Mass.	Recent	90.1	NG
Cod oil	Recent	92.1	M
Casein	Recent	92.5	M
Gelatin	Recent	91.4	M
CARBON OF VEGETABLE ORIGIN			
Linseed oil	Recent	92.8	M
Raw China wood oil	Recent	92.8	M
Rubber	Recent	92.5	M
Spores of *Lycopodium clavatum*	Recent	93.1	M
Weed. Tulsa, Okla.	Recent	92.6	W
Pine wood. Mass.	Recent	91.5	NG
Pine wood	Recent	91.6	M
Oak wood	Recent	91.6	M
Maple wood. Mass.	Recent	91.9	M
Peat. Frostproof, Fla.		92.8	M
Interglacial wood. Kittson Co., Minn.	50 000 y.	92.2	M
Wood. Moorhead, Minn.	Late Pleistocene	91.7	M
Wood	Pleistocene (1 m.y.)	91.9	M
Spruce wood. Springfield, Minn.	Pleistocene (1 m.y.)	91.8	M
Lignite. Siebenberg, Germany	Pliocene-Miocene	91.8	M
Xyloid lignite. Brandon, Vt.	Eocene	91.7	M
Lignite. Pastry, France	Cretaceous	91.9	M
Bituminous coal. Carillos, N. M.	Cretaceous	91.5	M
Jet. Whilby, England	Jurassic	91.3	M
Bituminous coal. Coal City, Ill.	Carboniferous	92.0	M
Bituminous coal. Waukee, Iowa	Carboniferous	91.6	M
Semi-anthracite. Antarctica		92.3	M
Anthracite. Kingston, Pa.	Carboniferous	91.4	M
Anthracite. Tenn.	Carboniferous (250 m.y.)	91.8	NG
Graphitized anthracite. Mansfield, Mass.		91.8	M

The values given in Table 2 are also plotted in Figure 4. It is evident that these samples also are distributed between two groups, one of which is represented only by sample No. 8 with $C^{12}/C^{13} = 88.4$ while all other samples have values very con-

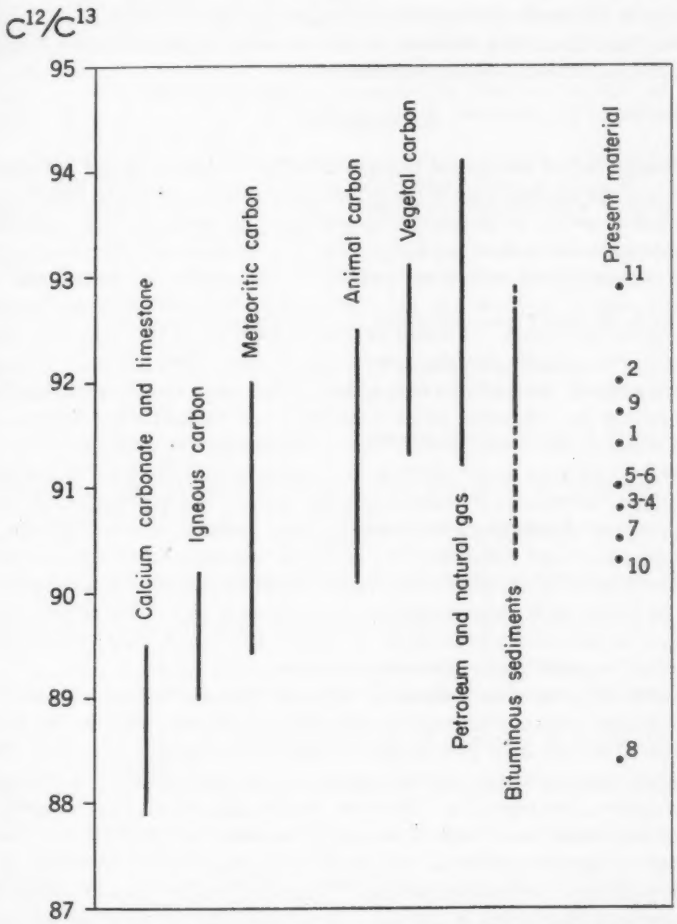

FIGURE 4.—*Distribution of the C^{12}/C^{13} ratio in materials of different origin*

siderably in excess of the former, ranging from 90.2 to 92.9. Sample No. 8 which represents graphite from a pegmatite contact in limestone falls within the inorganic range, while the others are well in the organic region. The geological interpretation of the graphite No. 8 as a product of reduction of CO_2 of the limestone agrees completely with the result of the mass spectrometric C^{12}/C^{13} determination.

The result for the shungite, 92.9, agrees quite well with the value obtained by

Murphey (1941), or 92.7. The high C^{12}/C^{13} ratio in this sample would seem to mean that heating by the diabase magma, suggested to be active in the formation of the first variety from the pelitic slates, did not have any notable action on the isotopic composition of carbon.

According to the results of the mass spectrometric work it seems to be safe enough to conclude that the carbon samples, except the contact graphite from Parainen, represent carbon formed by organic processes.

CONCLUSIONS

The investigation of the carbon isotope ratios has evidently settled the question of the origin of the material used in the present investigation, giving as definite proof as is possible according to our present knowledge. The series of bituminous shales may thus be followed back to the Early pre-Cambrian terranes where they are disguised as carbon-bearing schists and phyllites. The results also afford proof concerning the organic origin of the graphite deposits interbedded in pre-Cambrian metamorphosed sediments. It would lie close at hand to assume that, for example, the Mäntyharju graphite deposit, surrounded by gneiss was originally a layer of bituminous sediment from which nearly all other substances except carbon have been removed during the migration and metamorphism connected with the orogenetic processes whereby also the lenticular shape of the deposit was produced.

Further, we can make a rare contribution to Archean paleontology by concluding that *Corycium enigmaticum* Sederholm is a real fossil. The earliest trace of life on the Earth is thus definitely pushed back to Late Archean times. *Corycium*, the oldest fossil in the world, differs from the other old witnesses of life in that it consists of native carbon while the other forms represent carbonate relics in limestones and cherts. As to the other carbonaceous accumulations in the schists of the Tampere region, they too are evidently products of organic activity, but the original texture preserved in *Corycium* is no longer visible in them.

The results obtained in the present investigation seem apt to lead us to geological and geochemical speculations dealing with carbon. Future work on the isotopic distribution of carbon may give important results on problems related to oceanic geochemistry, sediments and sedimentary rocks, and geochemistry of mineral deposits, to quote a few examples. However, the present results seem to justify the conclusion that there would seem to be a slight decrease in the C^{12}/C^{13} ratio during the processes of metamorphism and metasomatism (graphitization), pointing toward the concentration of the heavier isotope, C^{13}, as is evident by the low values of the carbon-bearing schists given in Table 2. In addition, the range of the bituminous sediments (Fig. 4) may be enlarged to cover the C^{12}/C^{13} ratios from 90.2 to 92.9.

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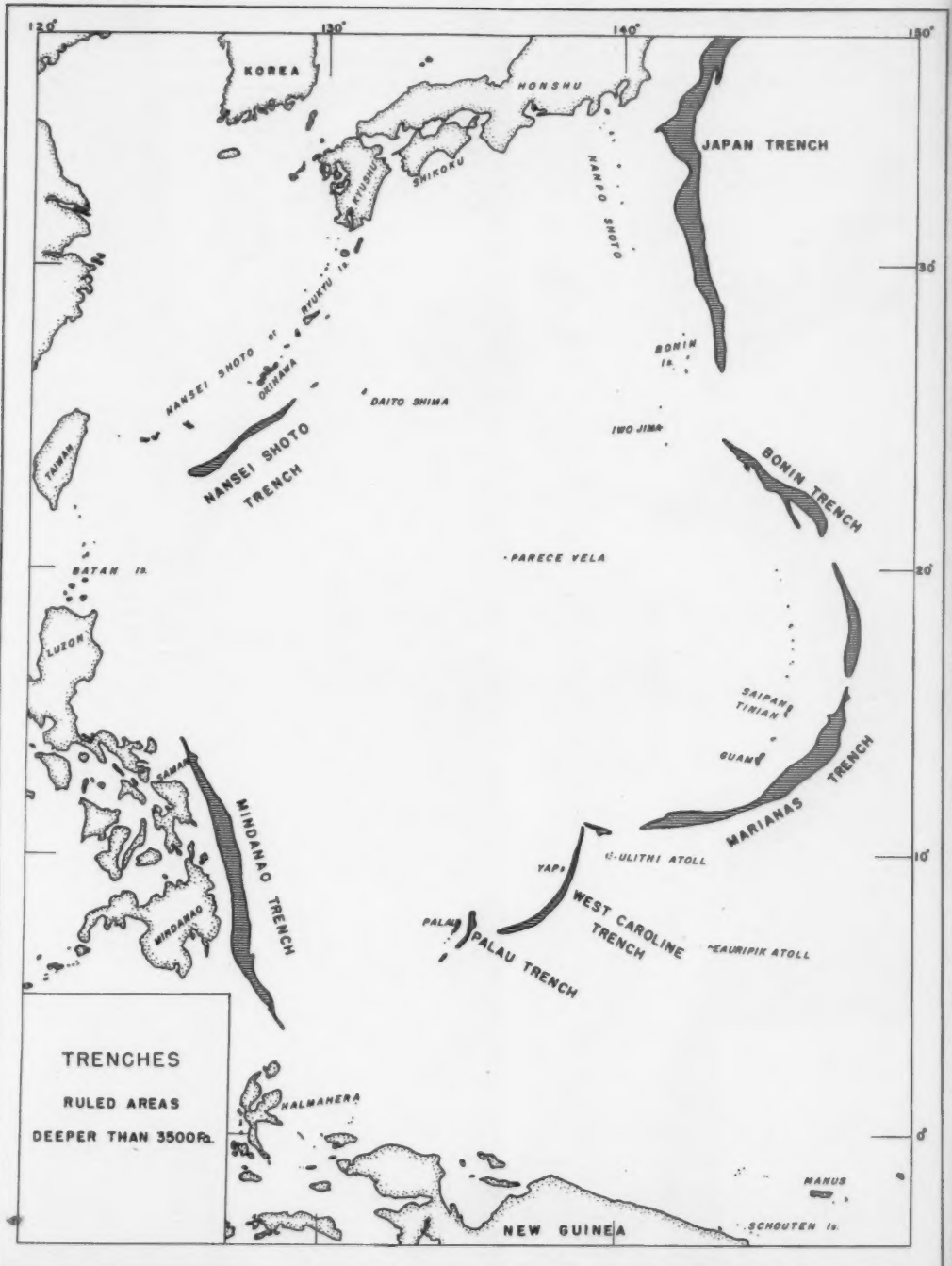
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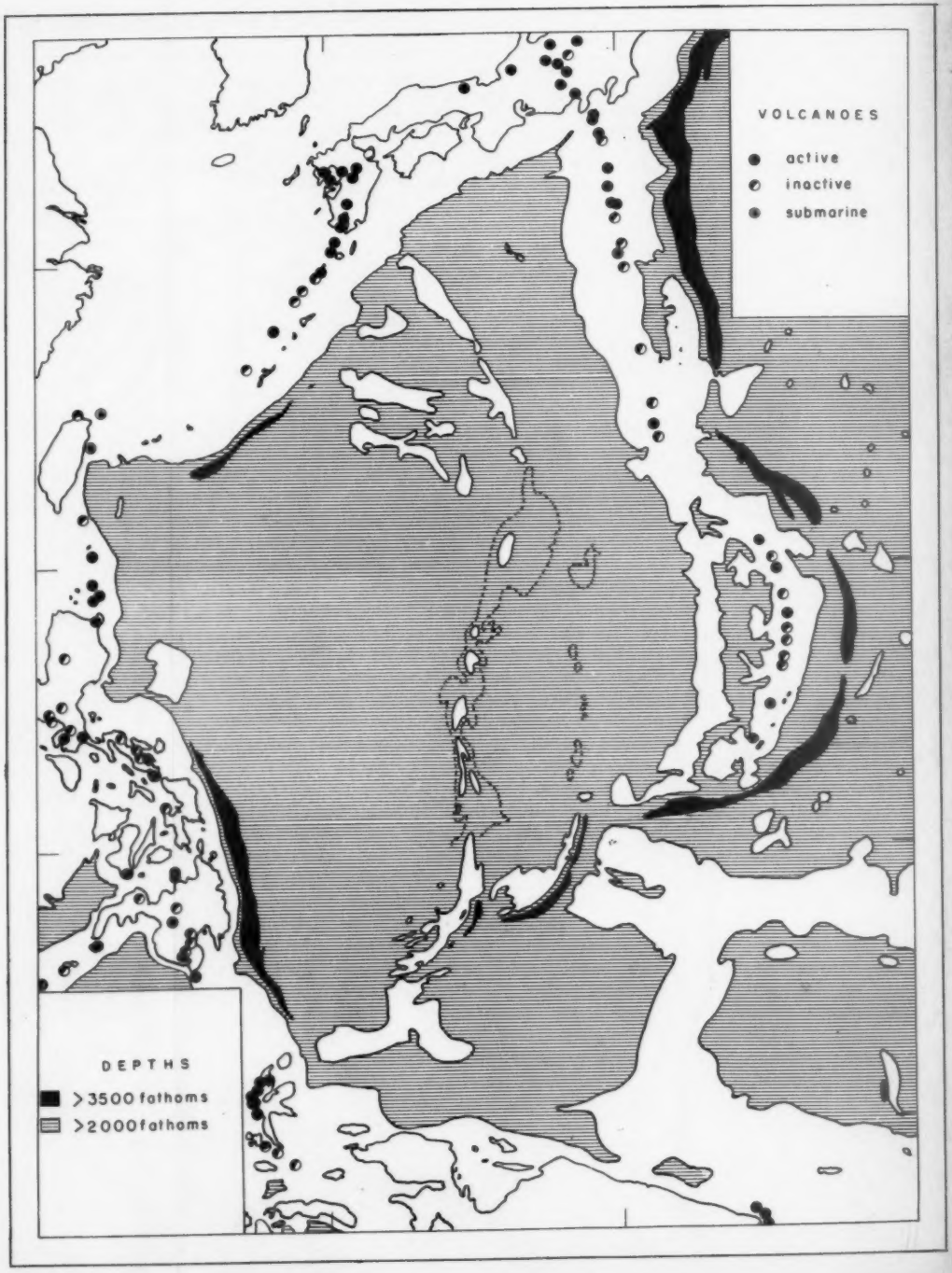
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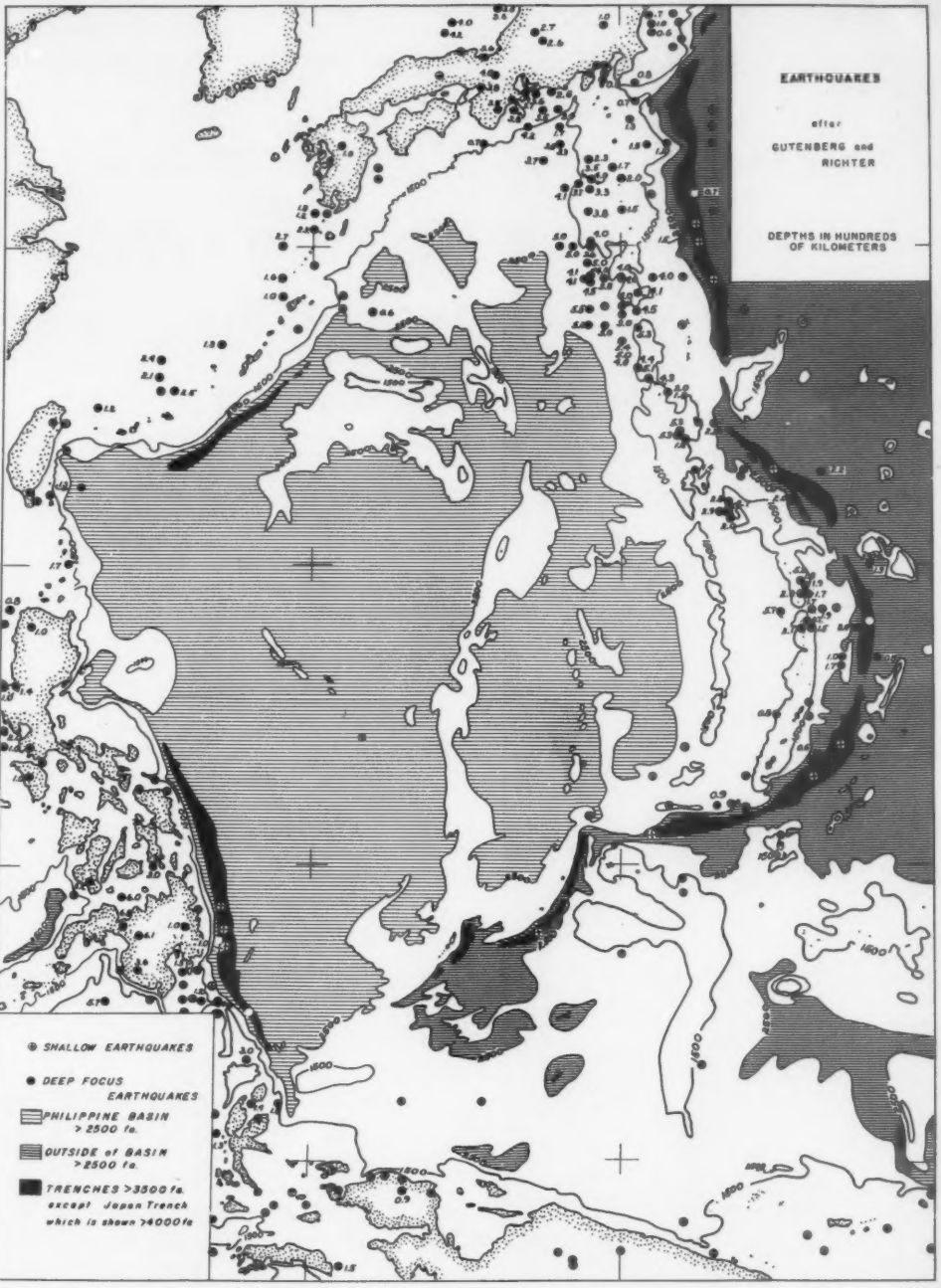

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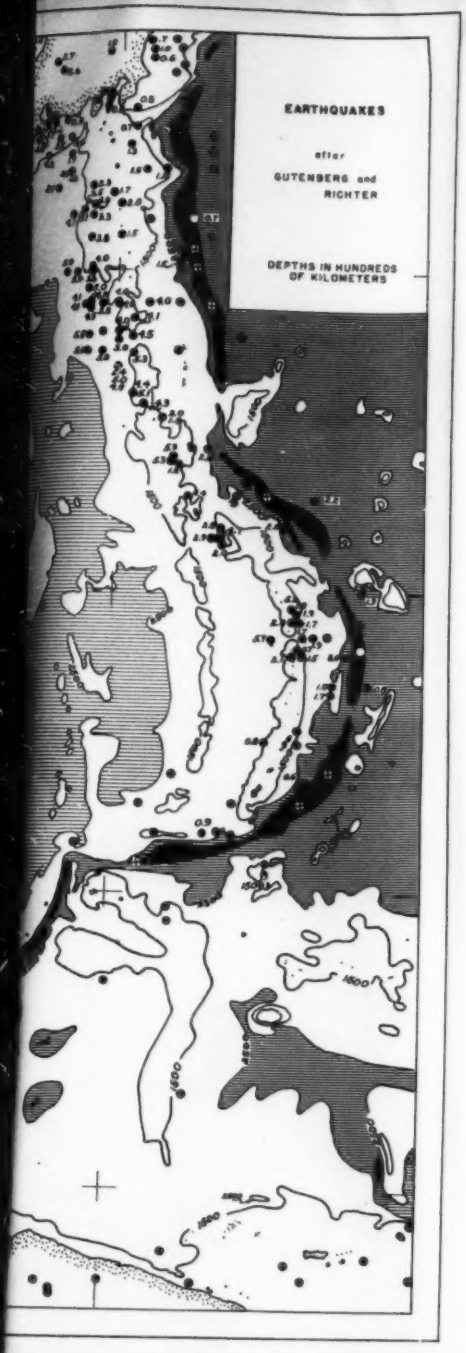

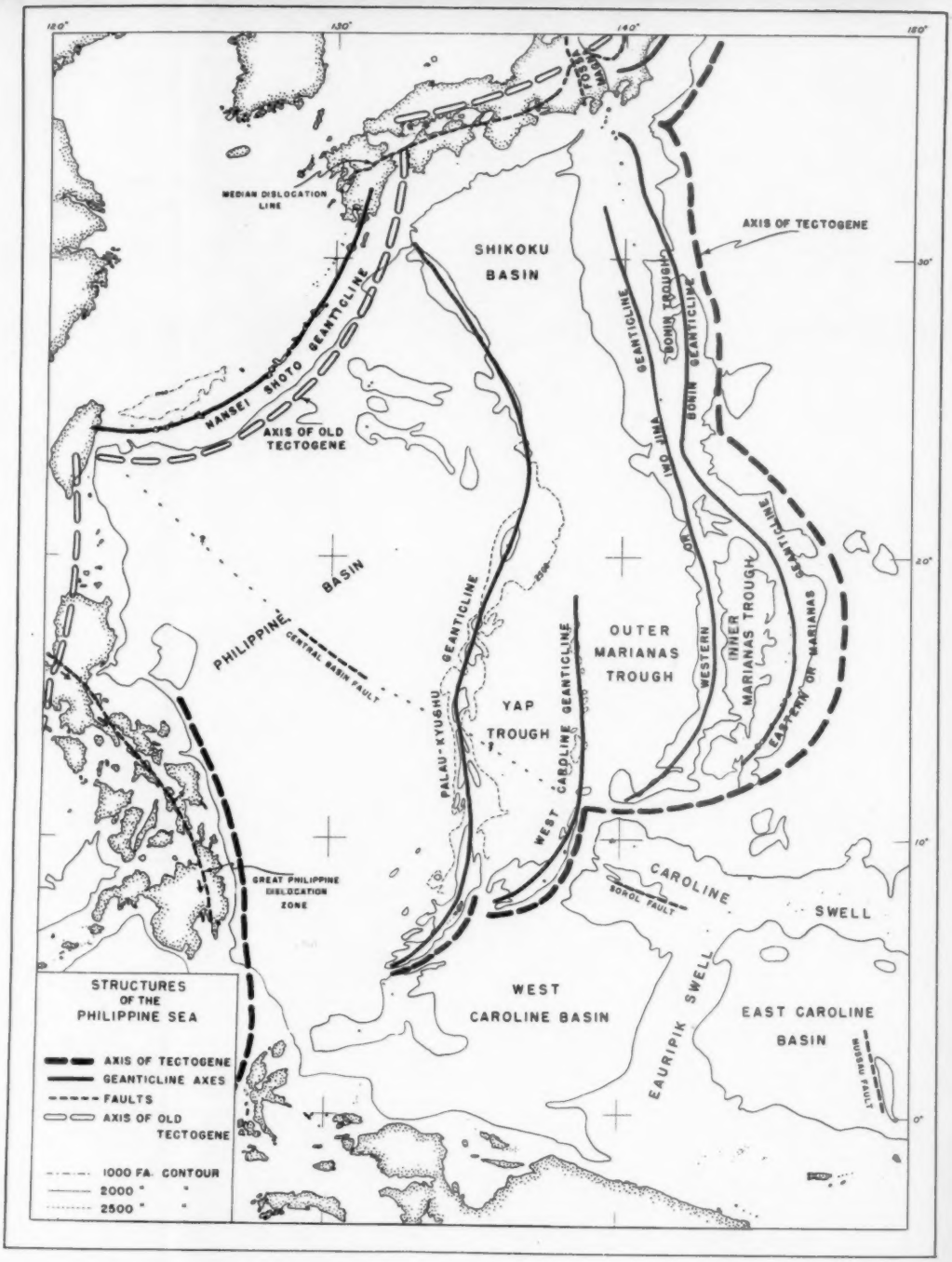

INDEX MAPS OF WESTERN NORTH PACIFIC

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MAJOR STRUCTURAL FEATURES OF THE WESTERN NORTH PACIFIC, AN INTERPRETATION OF H.O. 5485, BATHYMETRIC CHART, KOREA TO NEW GUINEA

BY H. H. HESS

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ABSTRACT

During the war the Navy accumulated a vast number of soundings in the Pacific Ocean. Many sounding lines crossed areas far from normal shipping routes and in

waters seldom traversed by ships. Combining these soundings with those already existing on Pacific charts it was possible to construct far more accurate and detailed bathymetric charts of the area than heretofore. The first of these charts to be printed by the Hydrographic Office U. S. Navy covers the area from Korea to New Guinea including within it the Marianas, the western Carolines, the Philippines, the Ryukyus, southern Japan, the Bonins, and the Volcanoes.

The great elongate, deep trenches form the most striking topographic and structural features on the chart. The deeps are much more continuous than was previously indicated. East of the deeps from Japan to Palau a portion of the North Pacific Basin province is portrayed which differs markedly in topography, structure, and petrology from the island-arc provinces to the west. The so-called "Andesite Line separates the North Pacific Basin province from the western island-arc provinces. The concave side of the curved deeps contains from one to three parallel geanticlinal swells on which volcanic islands are characteristic.

The vulcanism and seismic activity of the area are discussed. The geologic history of the region is outlined insofar as it may be surmised from fragmentary data. In general the eastern and southern belt of arcs and mountains is related to Late Cretaceous-Early Tertiary deformation which has continued spasmodically up to Recent time, whereas a western belt including southern Japan, the Ryukyus, Formosa, and the western Philippines is probably the product of mid-Mesozoic deformation. Both deformations have belts of periodotite intrusions associated with them.

INTRODUCTION

This paper accompanies a bathymetric chart of the area from Korea to New Guinea recently printed by the Hydrographic Office, U. S. Navy (H.O.5485). The construction of the chart was initiated under the administration of Rear Admiral G. S. Bryan, USN Retired, Hydrographer, and completed under the administration of Rear Admiral R. O. Glover, USN, present Hydrographer. Both Hydrographers had a keen personal interest in the construction of such a chart. The enthusiastic support of Guillermo Medina, Chief Engineer of the Hydrographic Office, of this project and others in which the Navy has contributed to fundamental science is acknowledged.

In order to obtain a distribution of the chart to scientists interested in oceanic areas, The Geological Society of America contributed funds to cover the cost of printing additional copies of the chart.[1]

The Committee for Geophysical and Geological Study of Ocean Basins of The American Geophysical Union initiated a program of co-operation between scientists interested in the study of oceans and the Hydrographic Office, U. S. Navy, about 15 years ago under the chairmanship of R. M. Field. The present bathymetric chart is one of the many outgrowths of this policy of co-operation which has proved to benefit science greatly. The training of scientists in the needs of the Navy and particularly in acquainting them with the operating conditions of ships at sea has also been of inestimable value to the Navy during the war.

SOURCES OF INFORMATION

In the preparation of this manuscript the writer gratefully acknowledges assistance obtained from Charles G. Johnson, U. S. Geological Survey, Edward Sampson,

[1] Additional copies of H.O. 5485 may be obtained from the Hydrographic Office, U. S. Navy, Washington, D. C., for 50 cents.

Princeton University, and John Rodgers, Yale University, for supplying certain critical details of geological relations in Japan and the surrounding region. The writer is indebted to Preston E. Hotz for drafting many of the illustrations accompanying this paper.

Though no exact count has been made, it is estimated that 95 per cent of the soundings on which the contouring of the chart is based were taken by U. S. Naval vessels, and a large proportion of these were obtained during war-time operations. Among the other sources of data are the following: U. S. Coast and Geodetic Survey charts in the waters of the Philippine Islands; SNELLIUS Expedition Reports in the area from Mindanao to northwestern New Guinea; British Admiralty and Netherlands charts of the northern coast of New Guinea; and Japanese charts of the area immediately south of Honshu and east of Kyushu. Published Japanese charts of most other oceanic areas have been based almost entirely on soundings taken from our Hydrographic Office charts.

A large number of U. S. Naval vessels obtained soundings in the area of the chart. The excellence of the work of some of these ships is particularly worthy of mention. The USS NERO in 1899 took 1000 wire soundings along traverses from Guam to Manila and Guam to Tokyo marking the beginning of investigation of bottom features in this area. In the 15 years preceding the war, the RAMAPO, operating as a supply ship between the west coast of the United States and the Philippines, obtained 60 sounding lines across the area. As a result of the RAMAPO's work, the general configuration of the floor of the North Pacific Ocean first became known. Though this was a magnificent achievement, the accuracy of the soundings is somewhat below present-day standards. Newer and more precise sounding lines, however, may be used to adjust the RAMAPO traverses.

During the war the battleship MASSACHUSETTS turned in more sounding information on the western Pacific than any other ship. This was accomplished while supporting carrier task forces and was largely under combat conditions. The battleship NEW MEXICO also took a great many soundings. The sounding data turned in by the following ships is worthy of mention; the cruisers NEW ORLEANS and CHESTER; the submarine BARB; the hospital ships SOLACE, BOUNTIFUL, and RELIEF; the survey ships SUMNER, PATHFINDER, and HYDROGRAPHER; and the transport CAPE JOHNSON.

CONSTRUCTION OF THE CHART

The mercator net for the chart was laid out by M. W. Buell, Jr., of the Oceanic Soundings Unit of the Chart Construction Division, Hydrographic Office. He also plotted many of the war-time sounding data. In this he was assisted by Mr. H. Waldron and the writer, then officer in charge of the unit.

Most of the original contouring was done by the writer and checked by Buell. As a guide to the types of contouring required in various parts of the area, the writer's experience at sea in the Western Pacific was most valuable. Thousands of miles of sounding traverses crisscrossing the area were obtained during the progress of amphibious operations in 1944 and 1945. From these data, including hundreds of miles of continuous fathometer recorder tracings, a fairly comprehensive sample of the character of the bottom features of the area was obtained. This could be used to

advantage in interpreting other data available at the Hydrographic Office, in evaluating the accuracy of these data, and in combining all the information in the construction of the present chart.

The original contouring was done on 18 existing H.O. charts or standard position plotting sheets, Mercator projections, with scales of 4 to 5 inches per degree of longitude. These were reduced photographically to the scale of the present chart or to approximately one fifth of their original dimensions.

The material was turned over to the chief of the Division of Chart Construction, L. M. Samuels, under whose guidance the construction of the final chart began. H. Hoyer skillfully and expertly redrafted the chart. The advice of C. V. O'Brien of the Chartography Section on matters of compilation and the helpful suggestions of F. G. Perkins of the Drafting Section on lettering and drafting are particularly appreciated. Redrafting completed, the chart went to the Lithography Division where the technical skill and long experience of H. F. Aldridge, Litho-reproduction Chief, played a large part in the final appearance of the colored chart. W. G. Plumtree of the Survey Section carefully edited the final proof. Many others, too numerous to mention, played some part in the making of the chart.

Five hundred fathom contours are shown on the chart with the exception of the first, or 500-fathom line. This was omitted because (1) its position was not well known over many portions of the chart, and (2) it was considered preferable to show the 100-fathom contour around certain banks and in the East China Sea. The 100-fathom contour appears as a dashed line.

The contours represent depths as measured by sonic sounding with an assumed speed of sound in sea water of 4800 feet per second. To obtain the true depth a correction must be added and can be taken from the table printed in the lower left-hand corner of the chart. The corrections are small for shallow soundings but fairly large for the great deeps. Since, in the latter case, the contours are on steep slopes they would not be shifted appreciably by adding the correction. It has been the policy of the Hydrographic Office to show uncorrected soundings on all of their charts of deep-water areas. This permits a ship taking soundings to compare the observations directly with the chart without referring to a correction table.

The soundings on the chart are also uncorrected values with certain exceptions commented on below.

The Nero Deep was found by the USS NERO in 1899 obtaining a wire sounding of 5269 fathoms which is the value recorded on the chart. The Mansyu Deep south of Guam was found by the Japanese vessel of that name and is also a wire sounding. The Emden Deep off Mindanao was found by the German ship EMDEN in 1927 by echo sounding. The value given on the chart is 5703 fathoms. Though this is uncorrected the Germans used a higher speed of sound in sea water than the assumed speed of 4800 feet per second used for all other soundings. It therefore should be revised to 5560 fathoms to be consistent with other data on the chart. Furthermore the writer doubts that this sounding should be accepted in light of the method by which it was obtained and because later investigations of the Dutch ship SNELLIUS and the USS CAPE JOHNSON, which agree with each other, do not confirm the depth found by the EMDEN.

MAJOR FEATURES OF THE KOREA TO NEW GUINEA AREA

DEEP TRENCHES

The most striking features of the bathymetric chart are the long narrow trenches which include within them the greatest oceanic deeps in the world (Pl. 1A). The Japan Trench enters the chart near its northeastern corner. It extends southward into the Bonin Trench and thence into the smoothly curving Marianas Trench. The southwestern end of the Marianas Trench abuts abruptly against the northern end of the small West Caroline Trench which in turn abuts at its southwestern end similarly against the Palau Trench. There has long been a question as to whether such arcs joined one another as "S" curves or at sharp angles. In these two cases there can be no doubt that they meet approximately at right angles. The Palau Trench structure terminates or dies out a short distance southwest of the island group from which it takes its name. From ths point there is a gap of 300 miles westward to the Mindanao Trench.

The series of trenches stretching from south of the Palaus to east of Japan is continued northward off the chart in the Kurile and the Aleutian trenches, so that the system of linked structures may be said to extend from Alaska almost to New Guinea, a distance of more than 6000 nautical miles.

The Mindanao Trench lies off the east coast of the Philippines starting off southern Luzon and extending southward beyond the southern tip of Mindanao. Though as previously mentioned the writer is inclined to doubt the validity of the Emden Deep which is usually cited as the greatest known depth in the oceans, it is nevertheless likely that the Mindanao Trench does contain the greatest of ocean depths. The maximum depth found by the SNELLIUS when reinvestigating the Emden Deep was 5560 fathoms (corrected) 2½ miles south of the Emden position, and the maximum depth found by the USS CAPE JOHNSON on a straight-line traverse passing 1½ miles south of the position of the Emden Deep was 5532 fathoms (corrected). The Planet Deep some 10 miles to the northeast is 5352 fathoms (corrected). The CAPE JOHNSON recorded a depth in excess of 5700 fathoms (corrected) about 45 miles north-northwest of the Emden Deep. Since all these values are being reinvestigated at the Hydrographic Office, further discussion of them will be postponed.

The Mindanao Trench has an uncommonly straight course from its northern end to 7° North Latitude; thence it bends slightly to the southeast. Gravity observations indicate, however, that the tectogene structure[2] does not partake of this southeasterly bend but continues southward to pass west of Halmahera.

There remains to be considered the Nansei Shoto Trench lying east of the Ryukyu Islands. This trench is much less sharply defined than the trenches previously discussed and has very little area with depths in excess of 4000 fathoms. It is also geologically considerably older than the other trenches. From available geological information, it seems likely that all the trenches except the Nansei Shoto owe their origin to structures probably initiated in late Cretaceous time. Probably the East Indian trenches are the same age, and another trench also of the same age once joined

[2] Downbuckling of the Earth's upper crust. *See* later references concerning this subject.

the East Indies with the New Britain Trench which lies off the southwest corner of the chart. In the case of the latter postulated trench, the forces which produced it have subsided to such a degree that it has risen isostatically to form the North Range of New Guinea. In contrast, the Nansei Shoto Trench is the only remaining remnant of a once-extensive system of trenches and island arcs whose structures it is suggested were developed in middle Mesozoic time. This is further discussed in a later section on the peridotites. This belt of deformation extends from Borneo up the Palawan Islands, through western Luzon, over the Batan Islands and northward to Formosa, thence along the Nansei Shoto or Ryukyu arc to Kyushu, through Shikoku and Honshu, into Hokkaido and Sakhalin, and northward into Siberia.

The trenches are the topographic expression of the dominant structural feature of the region, the downbuckling of the crust or tectogene. This structure, originally discovered and recognized by Vening Meinesz as a result of gravity determinations, is the core and essence of mountain building, and all other major structures as well as the volcanic activity and the seismic activity of the region, are subordinate to and related to it (Vening Meinesz, 1934; Kuenen, 1936; Hess, 1938; Griggs, 1939; Umbgrove, 1942). The writer has purposely avoided the use of the term "fore-deep" since it tends to place the cart before the horse by inferring that the island arc is the major feature and the trench subsidiary to it.

THE ANDESITE LINE

The Andesite Line was originally suggested to separate the region of predominantly andesitic vulcanism from the region of the oceanic basin of predominantly basaltic vulcanism. It was considered to separate the region of continental types of rocks—schists and granitic rocks also occur on the islands of the island arcs—from the region in which only oceanic rocks—olivine basalts, nepheline basalts, and smaller amounts of their differentiation products such as trachytes and phonolites—occur. It is evident now that it is also a major structural and physiographic boundary. Its position has been changed somewhat from time to time as more information has become available on the rock types on the numerous small isalnds of the western Pacific. The present writer adheres to the line as laid down in 1944 by Hobbs. With the aid of the bathymetric chart and recent information on some of the islands, it can be given a more precise position at some points. From Alaska to south of the Palaus it should follow the outer, convex side of the system of trenches. This position, rather than immediately outside the island arcs without regard for the deeps, permits it to be a valid structural as well as petrologic boundary. From south of the Palaus it should probably be extended southward and thence southeastward parallel to and off the coast of New Guinea, north of the Admiralty Islands and Northern Solomons to a point just south of Samoa and thence southward outside the Tonga and Kermadoc trenches. Its position southward from New Zealand remains uncertain but most likely it extends past a point somewhat east of MacQuarrie Island.

In the region of the bathymetric chart, it divides the area into an eastern portion representing provinces of the Pacific Basin proper and a western portion of island arcs and related smaller basins.

THE PACIFIC BASIN PROPER

General statement.—The Pacific Basin proper is a huge area including that large part of the Pacific Ocean bounded by the Andesite Line on the north and west and by the continental slopes of North America, South America, and Antarctica on the east and south. This region could no doubt be subdivided into many smaller physiographic and structural provinces when a more complete picture of the details of bottom topography become available. For the purposes of this discussion, division into two provinces of that portion of the Basin which lies within the limits of the chart are suggested.

North Pacific Basin.—This province is represented on the chart by a narrow strip extending from the northern border of the chart down its eastern margin to approximately 10° North Latitude. The southern boundary of the province is arbitrarily placed at the 2500 fathom contour which marks the northern flank of the Caroline Swell. The western boundary is represented by the Andesite Line which here follows the convex, eastern side of the trenches.

For the most part it is characterized by a level or very gently undulating bottom with depths near 3000 fathoms. It would appear from data now available that this province would extend with little variation over most of the North Pacific Basin. Below 28° North Latitude this otherwise almost featureless plain is dotted here and there by guyots, concial flat-topped peaks, described elsewhere (Hess, 1946). These are considered to be old truncated volcanoes. The flat tops of the guyots on the chart lie mostly between 800 and 900 fathoms.

Caroline Swell and Basins.—This province is bounded on the north by the North Pacific Basin and on the west and south by the Andesite Line. It extends off the chart to the eastward for about 500 miles to the eastern margin of the Caroline group.

This province is strikingly different from the North Pacific Basin area, and its features are remarkably similar to the swell and basin topography of the South Atlantic Ocean (Fig. 1). The Caroline Swell enters the chart at its eastern margin and extends across it in a westerly direction to the edge of the West Caroline Trench. It ranges from 100 to 200 miles in width and becomes two-pronged near its western end. This split in the swell may be the result of faulting since there is a steep northward-facing scarp just north of Sorol Island. The Swell rises with gentle slopes from the normal ocean floor to depths of from 1500 to 2000 fathoms and is no doubt structural. The atolls and islands of the Caroline group are perched on rather extensive banks which rise rather abruptly from the Swell.

Below Eauripik Atoll a prong or subsidiary swell extends southward to New Guinea. This, the Eauripik Swell, separates the West Caroline Basin from the East Caroline Basin. The West Caroline Basin is bounded by the already mentioned swells on the northeast and east and by the Andesite Line on the remainder of its circumference. The East Caroline Basin is bounded by the same swells on the north and west, by the Andesite Line on the south, and on the east, off the chart, by another swell which extends northward from the region of the Solomon Islands to the eastern end of the Caroline Swell.

These swells and basins are major structural features. The basins have smooth floors near 2500 fathoms in depth and probably are plains of deposition. The sim-

plicity and smoothness of the contours outlining Eauripik Swell might suggest generalized contouring of an area with few soundings; this, however, is not the case. The writer has used the 2000-fathom contour along the west side of the Swell on several occasions to obtain a line of position when navigating these waters.

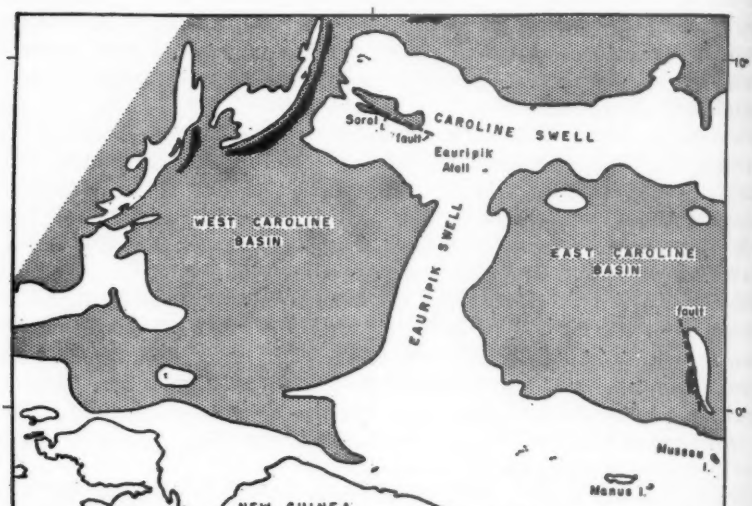


FIGURE 1.—*Caroline Swell and Basins subdivision of the North Pacific Basin*

Dotted area indicates depths in excess of 2000 fathoms, solid black indicates depths in excess of 3500 fathoms.

In the southeastern portion of the East Caroline Basin a narrow depression exceeding 3500 fathoms in depth is flanked by a rise with a minimum depth of less than 1000 fathoms. A northward-trending scarp separates the two. The scarp is probably much steeper than the somewhat generalized contouring would suggest. Unfortunately most of the sounding lines available in this area cross the scarp at a low angle so that no suitable transverse profiles are available. This is one of the very few places in the ocean, outside the trenches related to island arcs, where the depth exceeds 3500 fathoms. It is almost certainly a fault scarp. The high point on the rise is not opposite the low point of the depression but is about 60 miles north of it. This suggests either a scissorslike motion on the postulated fault or that the fault is a transcurrent one. The writer favors the latter hypothesis. In Plate 1D, the scarp is indicated as the Mussau fault; it is named after Mussau Island immediately south of it.

PHILIPPINE SEA AND SURROUNDING FRAMEWORK

This is a very complex area, bounded on the north and northwest by older, probably mid-Mesozoic, arcs and on the east and south by younger late Cretaceous-

Tertiary arcs. In Plate 1B delineation of the basins and ridges is brought out by shading of the depths in excess of 2000 fathoms. The inferred structural elements are shown separately on Plate 1D. A great swell 1400 nautical miles in length extends southward from the Tokyo Bay area of Honshu to the southern limit of the Marianas. This feature is clearly a double ridge in the Marianas area, but less evidently so in the Nanpo Shoto to the north. Here, however, it is fairly clear that the Bonins lie on an eastern ridge, and the Volcano Islands and their northward extension on a western ridge with a narrow depression, the Bonin Trough, between the two ridges, dying out north of 30° North Latitude. The swell is probably a double geanticline with eastern and western geanticlines coalescing at the junction of the Marianas and Bonins and diverging again to the northward. These geanticlines are surmounted by volcanoes, and their topographic expression has probably been exaggerated by the piling up of volcanic debris on their crests. The axis of the tectogene is indicated by a heavy dashed line in Plate 1D. Its position has been taken directly from the gravity results where available and elsewhere has been inferred from the topography (the deep trenches). The eastern, or Marianas-Bonin, geanticline and western, or Iwo Jima, genaticline are clearly related to the axis of the tectogene and represent great gentle folds of the crust on the concave, active side of the tectogene. This interpretation is further strengthened by reference to the gravity data south of Japan.

Similar geanticlines appear on the concave sides of the smaller West Caroline and Palau arcs. In these smaller arcs the geanticline is narrower and closer to the tectogene axis. The gravity anomalies found by Meinesz over the trenches are smaller too. These facts suggest that here the upper crust is thinner. Final analysis of this postulate must await a more detailed gravimetric survey of these small arcs. Both of the above-mentioned geanticlines extend far northward into the Philippine Basin. The westernmost one forms the Palau-Kyushu geanticline which stretches from Palau to southern Japan. (*See* Plate 1,C and D.) The eastern one, forming the West Caroline geanticline, is much less pronounced and only indicated by the 2500-fathom contour as a lineal series of oval-shaped rises which appear to die out 500 or 600 miles north of Yap Island. Thus four successive geanticlines can be identified behind the Marianas arc. The Palau-Kyushu geanticline has a single island on it near its midpoint, Parece Vela. Little is known of this island except that Tayama (1935a) lists it as a coral island.

On the northeastern side of the Philippine Basin, the Nansei Shoto, or Ryukyu, arc is a feature in many respects analogous to the Marianas arc, but older, higher, and having more deeply eroded islands. It is the only remnant in the area of the chart of the older, probably mid-Mesozoic, system of arcs. The remainder has risen to form large land areas such as Japan, Formosa, and the Philippines. The trench on its convex side barely reaches 4000 fathoms in its deepest parts, and its outlines have become somewhat indefinite compared to the younger trenches. No doubt the tectogene beneath it has largely if not entirely disappeared. A moderate amount of seismic and volcancic activity, however, still persists. The geanticlinal axis along the Nansei Shoto is shown in Figure 2, and for a comparison of this arc with the Marianas and the Lesser Antilles of the West Indies the reader is referred to Figures 3 and 4.

Three small islands about 150 miles east of Okinawa are the only islands, aside from Parece Vela, within the Philippine Basin. These islands—Okino Shima, Daito Shima, and Kita Daito Shima—project up to the surface from two short irregular ridges trending west-northwest. Hanzawa (1938) reports a number of borings on

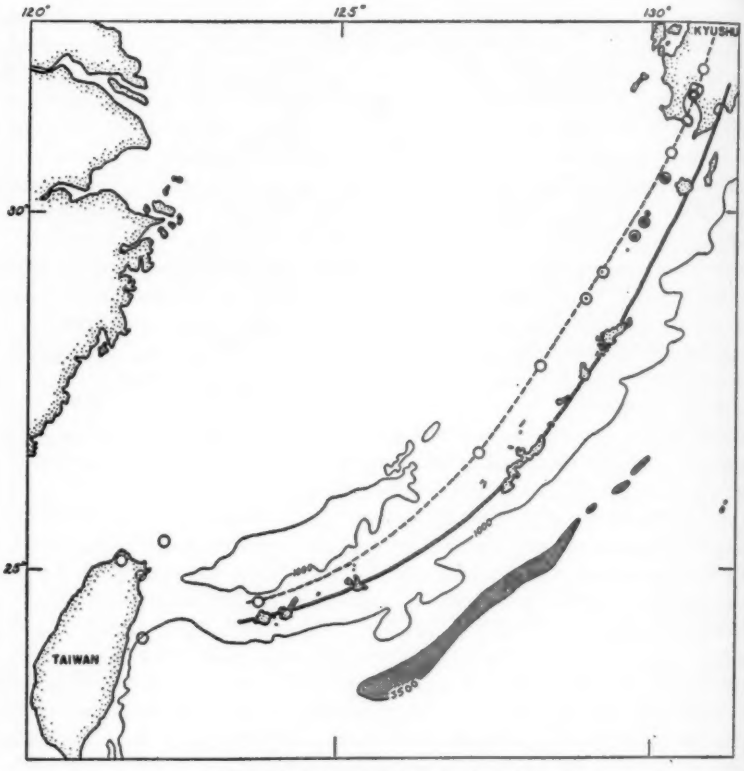


FIGURE 2.—*Nansei Shoto or Ryukyu Arc*

The geanticlinal axis is shown as a solid line, and volcanic axis as a dashed line. Circles indicate volcanoes. Compare with Figures 3 and 4.

Kita Daito Shima; the deepest is over 1400 feet. The borings penetrated organic limestones, calcareous muds, and sandstones. The upper portion of dolomitized limestone is correlated on the basis of Foraminifera with the Plio-Pleistocene Ryukyu limestone, and the lowest portion is thought to represent Lower Miocene and Upper Oligocene. The whole section is considered to indicate shallow, warm-water conditions of deposition.

Approximately in the center of the Philippine Basin (16° N. and 131° E.) a small elongate deep (3925 fathoms uncorrected) is flanked by much shallower water (Pl. 1,C and D). This is tentatively interpreted as a fault extending southeast-

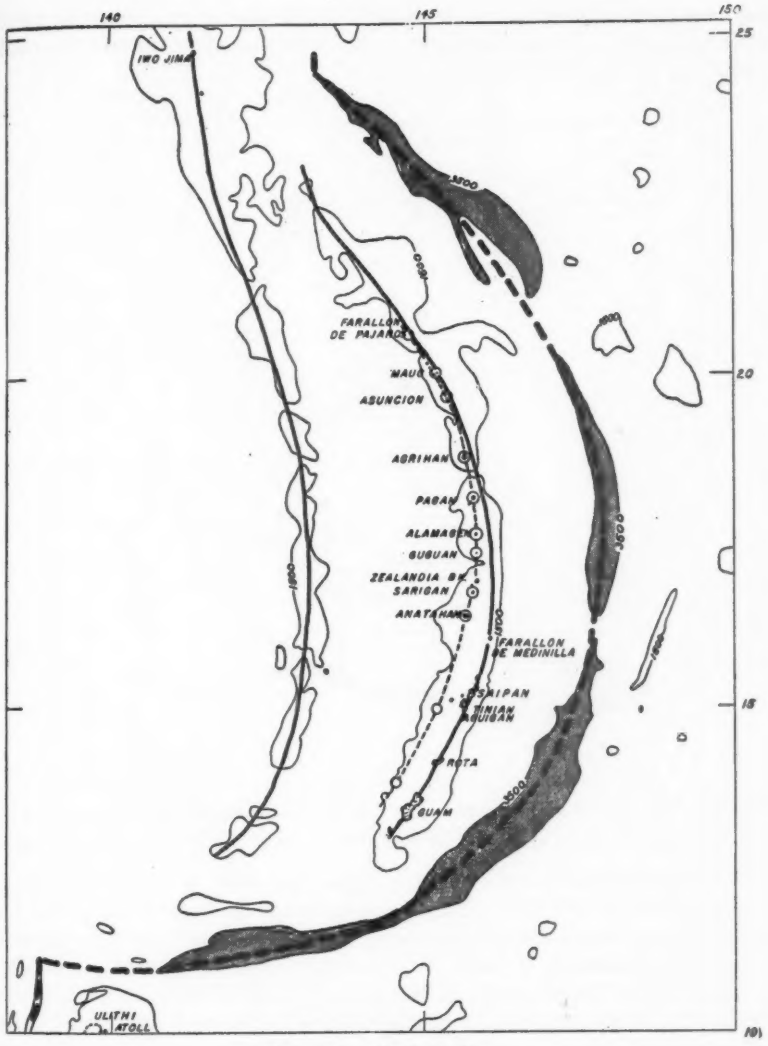


FIGURE 3.—*Marianas Arc*

Axis of tectogene appears as a heavy dashed line, geanticlinal axes solid lines, volcanic axis light dashed line, and volcanoes open circles. Note the departure of volcanic axis from the geanticlinal axis toward the south. The two southernmost volcanoes are submerged. The outer islands from Farallon de Mendinilla to Guam have terraces tilted to the west.

northwest. If this trend is extended to the northwest it terminates in the junction of the Nansei Shoto and Taiwan-Philippine arcs and if extended to the southeast it terminates in the junction of the Marianas and West Caroline arcs. This may be a

very important major shear zone of transcurrent faulting along which crustal blocks of the basin have adjusted themselves to the curving trends of the arcs along which the Earth's crust has buckled downward.

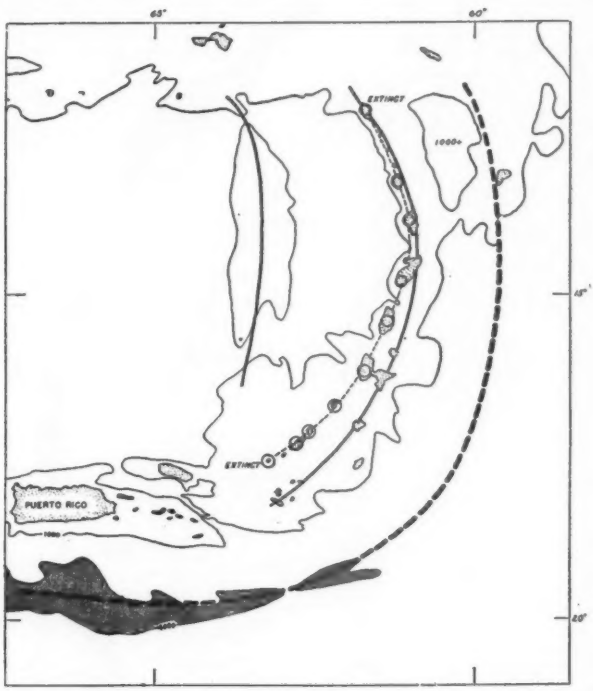


FIGURE 4.—*The Lesser Antilles inverted north to south for comparison with the Marianas (same scale)*
Similar structural features may be noted including the divergence of the volcanic and geanticlinal axes.

Along the margins of the Philippine Basin two great zones of dislocation are known, one in the Philippine Islands and the other in southern Japan (Pl. 1D). The Philippine zone is a striking topographic feature and may be traced along an almost continuous series of scarps from west-central Luzon to southern Mindanao. It may be easily located on the physiographic diagram of the islands. It is interpreted as a transcurrent fault, probably of large displacement, with the west side moving south. The Median Tectonic Line or Median Dislocation Line of southern Japan extends across northern Kyushu, central Shikoku, and onward into Honshu in nearly a straight line until it reaches the northward-trending structure of the Fossa Magna where it is bowed northward. It is a zone of thrust faulting with the overthrust moving south-southeast. Its straightness suggests a fairly high angle for the dip of the fault planes. The Median Dislocation Line is paralleled by the southern peridotite belt, and the northern peridotite belt, also parallel, lies 100 miles to the north along the far side of Honshu (Fig. 5). The two peridotite belts indicate the

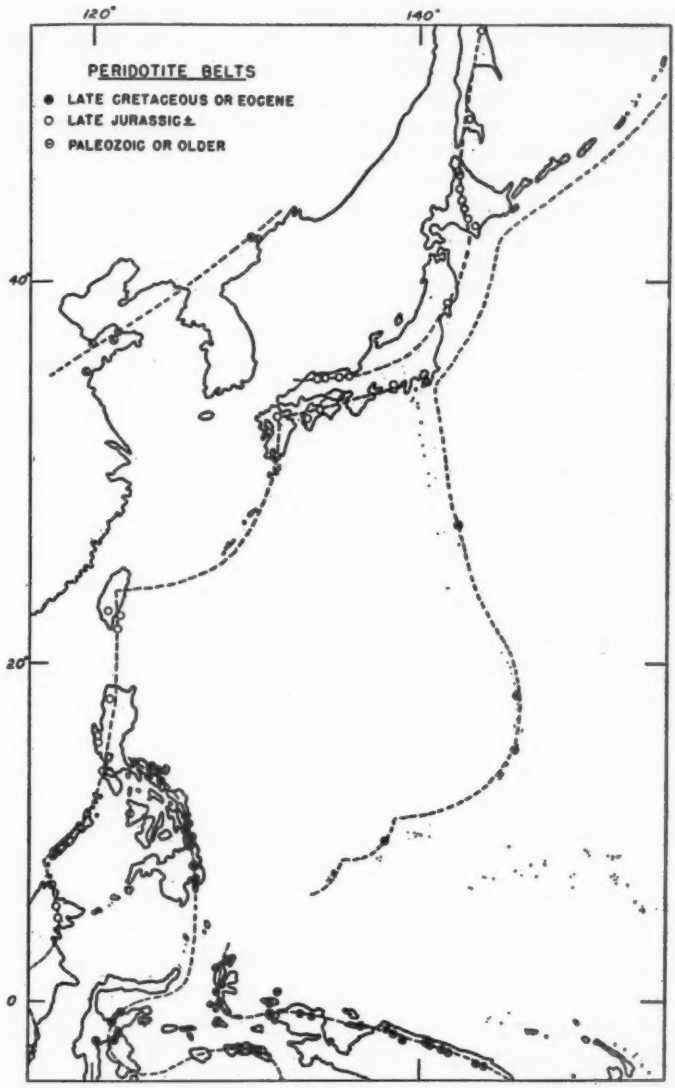


FIGURE 5.—*Peridotite belts*

margins of the geotectoclinal zone (the zone of intense deformation over the mid-Mesozoic (?) tectogene[3]). The Median Dislocation Line, also on the southern margin of the geotectoclinal zone, represents the plane along which material that had

[3] *See* Hess (1938) and Umbgrove (1934–1942) for discussion of terminology, and structures to be expected in this zone.

been carried down in the core of the tectogene and metamorphosed was later squeezed upward and thrust outward. The northward bowing of the Median Dislocation Line in the vicinity of the Fossa Magna is probably an effect of the younger, Late Cretaceous-Tertiary, deformation. The Fossa Magna depression, extending northward across Honshu, represents a continuation of the Nanpo Shoto structures. Its western margin is probably a thrust fault carrying rocks above the fault from the west to the east. Its eastern margin may be a flexure. The depression is probably a structural analogue of the Bonin Trough to the south. The gravity anomaly map (Fig. 9) brings out this relationship.

GEOLOGICAL NOTES ON THE SMALL ISLANDS FROM HONSHU TO PALAU

Southward from Izu Peninsula which lies southwest of Tokyo Bay, the Fuji chain of young, dominantly andesitic volcanoes form a long line of small islands. South of the Kazan Retto or Volcano Islands the western or Iwo Jima geanticline continues with many sharp peaks along its crest which may well be submerged inactive volcanoes.

The northern end of the Eastern geanticline is devoid of young volcanic activity. The Bonin Islands consisting of three island groups are located on this geanticline. According to Akagi (1930) the Hahajima group consists of andesitic lavas, agglomerates, and Eocene Nummulitic limestone (originally described by Yoshiwara, 1902). The Chichijima and Mukojima groups have massive brown boninite, agglomerates, tuffs, and Oligocene lithothamnium limestone. On Ototojima of the Hahajima group, Suzuki (1885)[4] reported serpentinized periodotite, a significant discovery. While the relation of the serpentine to the sedimentary rocks is not known, probably, as on Yap, it belongs to a basement series and is older than Eocene Nummulitic limestone.

The Northern Marianas from Farallon de Pajaros to Anatahan are volcanoes, also dominantly andesitic (Koert and Finckh, 1920; Tayama, 1936). Many of these volcanoes are active. The volcanic trend continues southward from this point but is submerged (Figs. 7, 10). East of the volcanic axis is an outer chain of islands, from Farallon de Medinilla to Guam which consist predominantly of bedded volcanics and intercalated limestones. Koert and Finckh (1920) report serpentines on Tinian and Agrigan (= Agrihan?). Tayama (1936) does not mention serpentine on Tinian but seems to be concerned mainly with the sedimentary column for which he gives the following sequence:

Recent oölitic limestone
Raised reef limestone
Red brown clay with ash
Marianas limestone (= Riukiu limestone? Plio-Pleistocene) unconformity
Carolinas limestone
Tinian beds unconformity
Miogypsina limestone (Lower Miocene)

[4] This reference in Japanese only; *see* Yoshiwara (1902).

Yellow tuffaceous sandstone (May lie either above or below the Miogypsina limestones)

Tayama (1938) gives a rather similar sequence for Saipan:

Recent limestone
Beach deposits
Raised coral reefs
Red brown clay
Marianas limestone (Plio-Pleistocene) unconformity
Naftan limestone (Plio-Pleistocene)
Tappocho limestone (Lower Miocene)
Donny beds. Tuff, sandstone shale
Densinyama conglomerate and tuff (Oligocene)
Matansyu beds
Hagman andesite
Sankakuyama liparite

Terraces are common on all the islands from Farallon de Medinilla to Guam and are tilted westward at the north end of the group and northwestward at the south end. These are described and figured by Hobbs (1944), and the observations are corroborated by the present writer. This disagrees somewhat with Tayama (1937). As may be seen in Figure 3 the volcanoes west of the above island chain are submerged. Considering this and the attitude of the terraces, it would appear that westward tilting in the southern Marianas has been accompanied by eastward shift of the geanticlinal axis. To the north where the geanticlinal and the volcanic axes converge and merge into a single line, westward-tilted terraces are not found.

The Yap group was described by Kaiser (1903), Koert and Finckh (1920), and Tayama (1935c). The unusual feature about this group is that the basement amphibolite and schist is exposed, and pebbles from it are found in overlying Miocene and younger conglomerates and gravels. Tayama lists the following rock types among the pebbles: amphibolite, actinolite schist, talc schist, gabbro, norite, diallage peridotite, and leucogranite. The strike of the schistosity is northeast. On the Palaus Tayama (1935b) finds various andesitic agglomerates and also limestones but no basement rocks. Sonsorol, Tobi, Merir, and Pulo Ana farther south are all low islands and probably coral. Krämer (1908) suggested that they are coral islands but did not examine them, and Tayama (1935a) shows them as such on a chart.

Thus the sedimentary islands (excluding those which are merely volcanoes) have various sequences consisting of tuffs, agglomerates, and limestones in large part, ranging in age from Eocene to Recent and resting on a basement of metamorphic rocks. None of the sequences are very thick, nor are they strongly folded. All of these features are characteristic of islands on the inner geanticlinal axis of young island arcs. The structural analogy to the Lesser Antilles of the Caribbean Sea is depicted in Figures 2 and 3, and the geological analogy is also close. On the Yap group older rocks are exposed including schists and peridotites. Serpentinized peridotites have also been reported on one of the Bonins and two of the Marianas. No sedimentary rocks dated as Mesozoic have been found on any of the islands. The

absence of determinable Mesozoic sediments, the presence of Eocene and younger Tertiary sedimentary rocks in an unmetamorphosed and not strongly, folded state, the occurrence of schists below Tertiary sediments on one island in the Yap group, and the presence of ultramafic intrusives probably belonging to the basement on four islands suggest the following history. The strong deformation which initiated the buckling of the crust preceded deposition of the Eocene Nummulitic limestone but followed deposition of the materials which form the schists of the Yap group. The metamorphism and the intrusion of the ultramafic igneous rocks accompanied the deformation. Inasmuch as no unmetamorphosed Mesozoic rocks are found this suggests, though the evidence is far from compelling, that the schists represent rocks of this age and that the deformation took place not long prior to the deposition of the Eocene Nummulitic limestone, possibly in late Cretaceous.

The dating of the older belt of deformation through the Japanese Islands, along the Nansei Shoto to Formosa and thence through the western Philippines and the Palawans, could possibly be done if one had a thorough knowledge of the Japanese iterature and a critical judgment of the many geologists who contributed to it. It is a literature replete with irreconcilable data and statements of relationships, which is understandable since it deals with an area of great complexity. An attempt will be made to do it on the basis of a short-cut method suggested by the writer some years ago (Hess, 1937)—namely, by using the periodotite intrusions.

PERIDOTITE BELTS

The writer pointed out that the peridotite intrusions in mountain belts can be an important tool in the hands of geologists because of certain pecularities of their histories and loci of intrusion. Peridotites of the ultramafic magma suite occur in all alpine type mountain systems and nowhere else. They occur in two belts about 50 miles on either side of the original location of the tectogene axis and less commonly in the area between the two belts. They are intruded during the first great deformation of the belt, presumably during buckling of the crust, and later deformations of the same belt are not accompanied by intrusion of peridotites. Thus ocation of the peridotite belt and dating its intrusion locate the old tectogene axis and date the initiation of the deformation of that zone. Applying this generalization to the older belt of deformation in the area under consideration the following relations are observed (Fig. 5).

The peridotite belt of the older zone of deformation is fairly continuous through the Japanese islands, Formosa, western Luzon, and the Palawans. It is a double belt in southwestern Japan, but elsewhere only one belt is exposed. No peridotites have been reported between Kyushu and Formosa, in the Ryukyu Islands, so far as the writer is aware. Glaucophane schists are, however, described in the southern Ryukyus, and such schists are almost invariably associated with peridotites. From Sakhalin the peridotite belt appears to continue northward into Siberia, and southward from the Palawans it swings through Borneo, into the Malay States, and probably into eastern Burma.

This belt, many thousands of miles long, may well represent a single zone of contemporaneous deformation, but the geological information necessary to support this proposition is at present scanty. In the Japan to Philippines section the belt can be

roughly dated as having been intruded at some time between middle Triassic and the end of the Jurassic. The single case of precise dating along the belt comes from Hokkaido where the peridotites are said to intrude the Jurassic and are younger than certain Cretaceous sediments (Edward Sampson, personal communication).[5] If this is their age, a correlation in time may be noted between them and the Nevadan peridotite belt of the west coast of the United States, a suggestion of interest to those who believe in the contemporaneity of great circum-Pacific orogenetic epochs.

In Shikoku the peridotites intrude the Sambagawa Series immediately south of the Median Dislocation Line, but the age of this series is uncertain. General opinion seems to be that the peridotites were intruded during the deformation of these rocks and that the peridotites themselves were deformed in the later stages of the orogenesis. Kobayashi (1938) shows that the deformation of this zone is pre-Inkstone Series (Lower Cretaceous). The writer concludes that slim evidence suggests an age for this peridotite belt equivalent to the Jurassic-Cretaceous boundary, but an older age within the Mesozoic is possible. The belt will henceforth be referred to as the mid-Mesozoic belt. Thus having located the peridotite belt and roughly estimated its age, we have thereby located the axis of the old tectogene and roughly date the time of its initiation.

The younger peridotite belt is well exposed in New Guinea and the eastern Philippines. It is poorly exposed in the arcs from Palau northward where the islands are small and have not been eroded deeply enough to cut through the overlying, younger Tertiary rocks. The occurrence of peridotite is well described for the Yap group. It is definitely present in the Bonins, but its relations to its enclosing rocks are poorly described. For the Marianas we have only hand-specimen descriptions. The next known appearance of peridotites northward along the belt from the Bonins is on Kamchatka though they may be present in the poorly explored Kuriles. The existence and location of the belt is thus fairly well established, and its age is probably not far from the Cretaceous-Eocene boundary. A long-range speculation might correlate this belt and its orogeny with the Laramide in North America.

A belt of old peridotite intrusions extends through Shantung peninsula and northern Korea. These are variously dated as pre-Cambrian or Paleozoic. The writer has at present no basis for any opinion as to their age.

VOLCANIC ACTIVITY

Plate 1B shows the location of volcanoes within the area of the chart. The data were largely taken from compilations of Von Wolff (1929) and Sapper (1917) with a small amount of additional information obtained on submarine eruptions from H. O. charts and files. For those volcanoes indicated as extinct or inactive, the main criterion was whether they retained the outward physical form of a volcano—a more or less conical shape and a crater. Such inactive volcanoes would probably be late Pleistocene or younger. A related group of volcanoes clustered around one center are shown by a single symbol.

[5] This statement is based on data from Japanese geologists working in that area. The age of the intrusion is placed approximately at the Jurassic-Cretaceous boundary.

The late Cretaceous-Tertiary belt of deformation is commonly paralleled by a belt of volcanic activity on the concave side of the tectogene axis and about 100 miles distant. The older belt of deformation, of mid-Mesozoic age, shows very much less activity, as might be expected; in fact, intense volcanic activity is limited to the northern half of the Nansei Shoto and Kyushu. Elsewhere along this belt activity is now slight or lacking, though in the latter part of the Mesozoic it probably extended along the entire belt as indicated today by old volcanics.

In the late Cretaceous-Tertiary belt from Tokyo Bay to the southern end of the Palau arc, a marked diminution of activity can be noted from north to south. The northernmost 300 or 400 miles, the Nanpo Shoto, has intense activity. From here to the Marianas along the Kazan Retto (including Iwo Jima), activity is mild. In the northern Marianas there is considerable activity, but south of latitude 18° the only indications of activity consist of a sulphur boil about 25 miles west of Saipan in 1944 and the presence of a submarine volcanic cone northwest of Guam which has not been known to have been active. Continuing from Guam to the southwestern end of the Palau arc no evidence of recent vulcanism is apparent.

The double geanticlinal structure of the swell from the Nanpo Shoto to the southern end of the Marianas has already been pointed out. The volcanic activity on the northern half of this structure is on the Western or Iwo Jima geanticline with no activity on the Eastern or Bonin geanticline. In the Marianas the situation is reversed—all the activity is on the Eastern or Marianas geanticline, and none on the Western geanticline. A comparison of the position of the volcanic trend with the position of the geanticlinal axis for the Marianas, Lesser Antilles of the West Indies, and the Nansei Shoto is made in Figures 2–4.

In the Philippines the intense activity in southeastern Luzon is related to the younger belt of deformation. The activity continues southward through Samar and central Mindanao and thence to the line of active volcanoes of Celebes. Intense activity appears on the eastern side of the tectogene in and near Halmahera. The activity continues along the East Indian chains via the Banda arc, Java, and Sumatra. Eastward from Halmahera along the northern coast of New Guinea there is another belt of late Cretaceous-Tertiary deformation but no volcanic activity for more than 1000 miles up to the Schouten Islands. The first of this group of volcanoes appears on the lower margin of the chart. This volcanic trend extends over the Schouten Islands and along the island of New Britain. New Britain has a large number of active volcanoes. It is interesting to note that a great portion of the circum-Pacific belt of late Cretaceous-Tertiary deformation which was initiated by an intense diastrophism, possibly synchronous along the entire belt, now presents a large degree of variation in the stage of its tectonic development. Some segments, such as the portion of the New Guinea coast just mentioned, have reached an advanced stage and been uplifted to form great mountain systems, whereas others such as the adjacent East Indian arcs and Schouten-New Britain arc, or farther north the Marianas and Nanpo Shoto, are still in a youthful island arc stage not very different from when they were first formed. The older Nansei Shoto, a product of mid-Mesozoic deformation remains in a relatively youthful tectonic stage, while the much more recently deformed New Guinea coastal area has reached a late stage of tectonic development.

This late stage is characterized by the rising of the belt to form high mountains and the disappearance of volcanic activity and of most of the seismic activity with the exception of sporadic shallow shocks.

Sporadic volcanic activity in the vicinity of Formosa, the Batan Islands, and western Luzon may be related to the older, Mid-Mesozoic zone of deformation, perhaps revived in younger orogenic epochs.

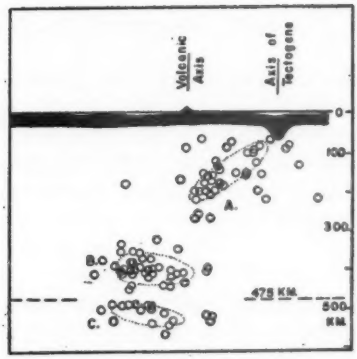
SEISMIC ACTIVITY[6]

A concentration of shallow earthquake epicenters may be noted over the tectogene. Those of moderate depth (60 to 200 kilometers) lie for the most part on the concave side of the curve of the tectogene and 100 to 250 kilometers from it (Pl. 1C; Fig. 6). This places the foci of moderate depth almost under the axis of volcanic activity, but perhaps a little displaced on the average toward the tectogene. Also, where there is considerable seismic activity at moderate depth in the region, there is considerable volcanic activity above it. In other regions such as the Aleutians and Lesser Antilles, the volcanic activity may be quite strong but unaccompanied by seismic activity at moderate depth below it. The seismic activity is evidently not directly related to the volcanic activity, but each is related to a common cause which appears to be the buckling of the crust—the tectogene.

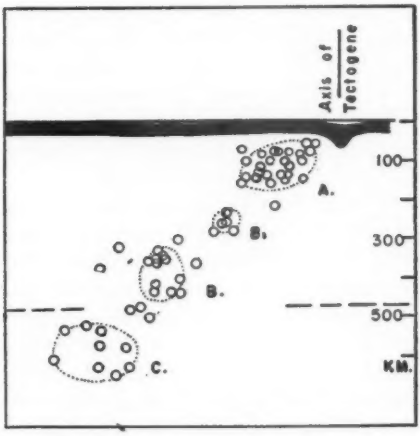
It has been postulated that the moderate and deep-focus earthquakes are located along approximately a 45-degree shear plane extending downward from the base of the tectogene (Coulomb, 1945; Schwinner, 1941; Wadati, 1940; Visser, 1937). In regard to moderate-depth earthquakes, this appears to be a valid working hypothesis. These at least roughly maintain such a position with regard to the base of the tectogene. A few foci are found approximately on the other possible 45-degree shear plane extending downward toward the convex side or in this case toward the Pacific Basin. The very deep-focus earthquakes do not appear to fit the postulate though many of them do occur in such a position that they might be attributed to a continuation of the 45-degree shear from those of moderate depth to 600 or 700 kilometers. The exceptions are such that, in the writer's opinion, they throw doubt on the hypothesis insofar as the deep group are concerned.[7]

The deep-focus earthquakes of the Kamchatka-Kurile arc lie parallel to and 400 to 600 kilometers west of the axis of its associated deep (Fig. 7). At the southern end of the Kurile arc, the deep, the volcanic activity, the shallow and moderate-depth earthquakes, and the exposed geologic structures all bend abruptly southward following the east coast of Honshu. But the deep-focus earthquakes continue the curve of the Kurile arc to the southwestward into the continent of Asia in complete disregard of the shallower structures and activities. Similarly the deep-focus earthquake trend below and west of the Nanpo Shoto arc, south of Honshu, continues to the northwestward disregarding the fact that the shallower structures turn northward to meet those coming down from the Kuriles off Honshu. The junction of the two deep-focus trends at a point in Manchuria just north of Korea results in an area of exceptionally intense deep-seated seismic activity.

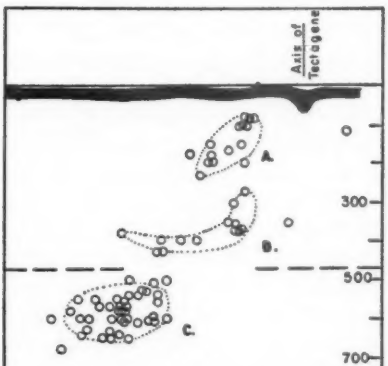
[6] Date from Gutenberg and Richter (1938; 1939; 1941; 1945).
[7] This will be considered in a future paper.



A. Composite profile Guam to Honshu



B. Composite profile Kurile Islands



C. Composite profile Tonga-Kermadoc Islands

FIGURE 6.—*Composite profiles showing relation of deep-focus earthquakes to the axis of the trench or tectogene in each of three island arc groups*

In Figure 6a, a composite cross section of all the moderate and deep-focus earthquakes given by Gutenberg and Richter for the belt extending from the south end of the Marianas to the north end of the Nanpo Shoto, a distinct gap of about 100

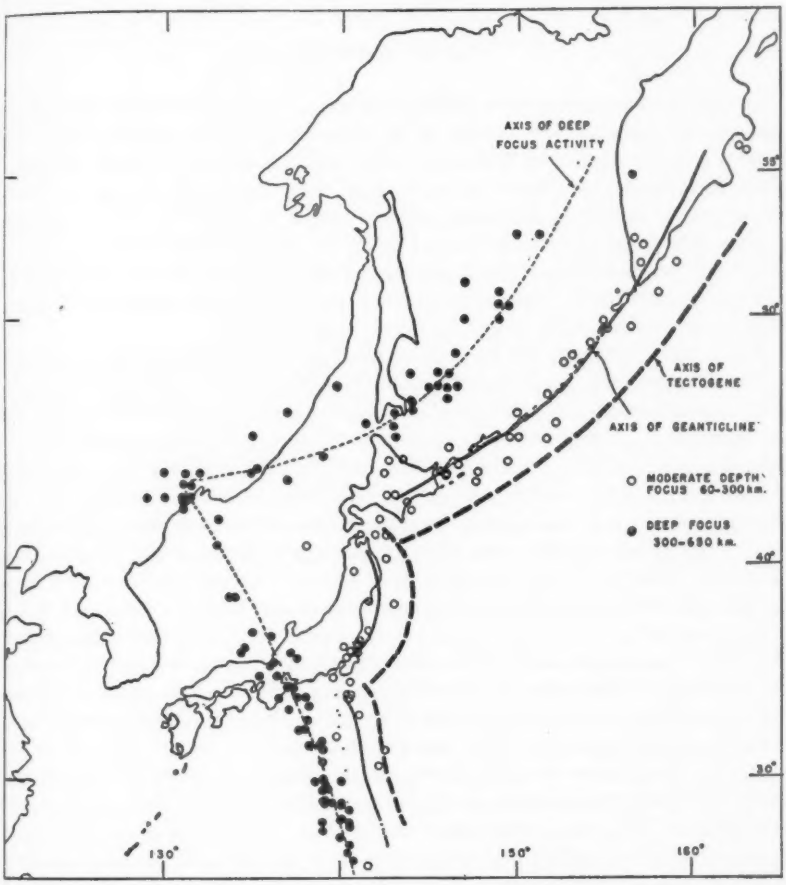


FIGURE 7.—*Divergence of the deep-focus seismic activity from activity at moderate depth*

kilometers depth may be noted between the moderate depth group (A) and the deep group or groups (B and C). A cross section of the Kurile Islands arc also shows a distribution in three groups. As noted, the deep groups continue on smooth curves the Nanpo Shoto and Kurile trends until they meet under Manchuria in a small zone of intense deep-focus activity, while the moderate-depth earthquakes diverge and follow the surface structures (Fig. 7).

In reanalyzing Gutenberg's and Richter's data it was noted that there are very few deep foci at or near 475 km. but quite a large number on either side of this level.

This may be seen in Figure 6 as indicated by the gap between groups B and C. Jeffreys (1936) has suggested a discontinuity at 481 ± 21 km., the co-called 20° discontinuity. The distribution of deep-focus earthquakes seems to offer some independent support for a discontinuity or a transition zone at this depth.

GRAVITY ANOMALIES

One hundred and twenty-two gravity stations on Japan and 80 observations at sea made by Matuyama (1936) present an excellent picture of the regional gravity field from the Bonin Islands to Hokkaido. Hayford isostatic and a series of regional isostatic anomalies have been computed for all these stations by Heiskanen (1945). These results have been contoured and are shown in Figure 9. This is the only portion of the area of the chart which has sufficient gravity information to permit a structural interpretation. The interpretation can, however, be extended with the aid of stations taken by Vening Meinesz on a traverse across the southern half of the chart, to cover most of the area of the chart in a general way.

Lejay (1939) has made 205 gravity observations on the Philippine Islands, but it is rather difficult to use these without knowing more about the variations in the gravity field over the water areas around the islands and without the corrections for isostatic compensation. Vening Meinesz's East Indian gravity net extends a short distance into the southwestern corner of the chart. Since this area has been thoroughly discussed by Vening Meinesz, Umbgrove, and Kuenen (Vening Meinesz, 1934) the small portion of it extending into the present chart will not be discussed at length here. It may be noted, however, that the strong negative anomaly belt of the East Indies lies between Celebes and Halmahera and trends northward so that it enters the Mindanao Trench off the southern tip of Mindanao Island. The trench departs from a southerly course and curves to the southeast to pass east of Halmahera. The negative anomaly belt and the axis of the trench diverge from each other at the southern tip of Mindanao. An investigation of gravity over the Mindanao Trench and surrounding area would be desirable, particularly if coupled with the use of Lejay's observations on the Philippine Islands.

Figure 9 represents the contoured isostatic anomalies (Hayford, d = 40 km.) computed by Heiskanen from the Japanese observations. Heiskanen gives a full discussion of these values and their relationships. A number of interesting correlations with topographic features on the chart may be noted. The axis of the negative anomaly belt corresponds very closely to the axis of the trench from the Bonins to Honshu. Normally the anomaly axis lies on the island side (concave side) of the axis of the deep or less commonly it lies along a ridge flanked by deeps. That the anomaly axis does not normally coincide with the axis of a trench can be accounted for by two factors, neither of which apparently was operative in the area under discussion. (1) Sedimentation from the islands, particularly if they are large, tends to fill the deep with deposits which build outward into the trench from the island side thus displacing the axis of the trench outward but not affecting the gravity axis very much. (2) Upsqueezing of material out of the core of the tectogene results

in a negative anomaly axis over a ridge flanked as a rule by deep water. Such is the case south of Sumatra and Java and also in the vicinity of Barbados in the West Indies. It appears that the trench from the Bonins to Honshu has a rather simple superficial structure which has been disturbed neither by sedimentation nor by upsqueezing of material from the core of the downbuckle. Farther north off the

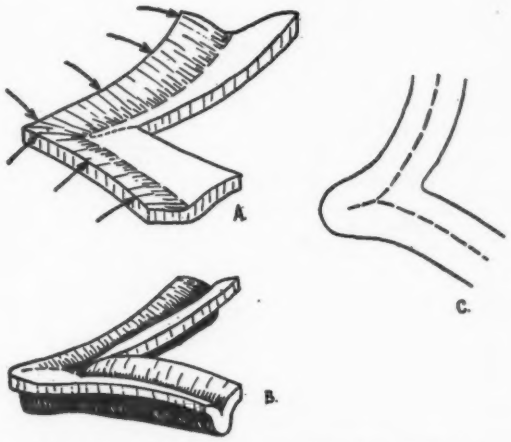


FIGURE 8.—*Development of a prong by downward buckling of synclines which meet at an angle*
This feature is shown topographically at the junctions of trenches and also in the gravity field.

larger islands of Japan, the negative anomaly axis lies on the landward side as might be expected.

Heiskanen points out that there are two inward bulges of the negative strip, one south of Tokyo and the other between Honshu and Hokkaido. These inward projections come at the points where the Nanpo Shoto arc meets the Honshu arc, and where the Honshu arc meets the Kurile arc. The topographic expression of the trenches at the junctions of the Marianas arc with the West Caroline and the West Caroline with the Palau indicate unequivocally that these junctions occur at sharp angles. The gravity anomalies show that the structure at depth is also of this character. Figure 8 illustrates how such a structure will develop provided the initial downwarpings meet at a sharp angle. As downward buckling progresses the forward motion is mechanically easier from the concave side, and in all island arcs examined the concave side gives evidence of having been the active one. Thus the farther the concave side rides forward and downward into the tectogene, the more pronounced will become the prong extending inward between the two arcs.

The Eastern geanticline from the Bonin Islands northward is represented in the gravity field by a strong positive axis, showing that it probably represents an upbowing of the crust and that it is truly geanticlinal. Where the negative prong extends inward (off Tokyo Bay), the positive axis dies out, but it reappears north of the prong in a homologous position and continues northward for the length of Honshu.

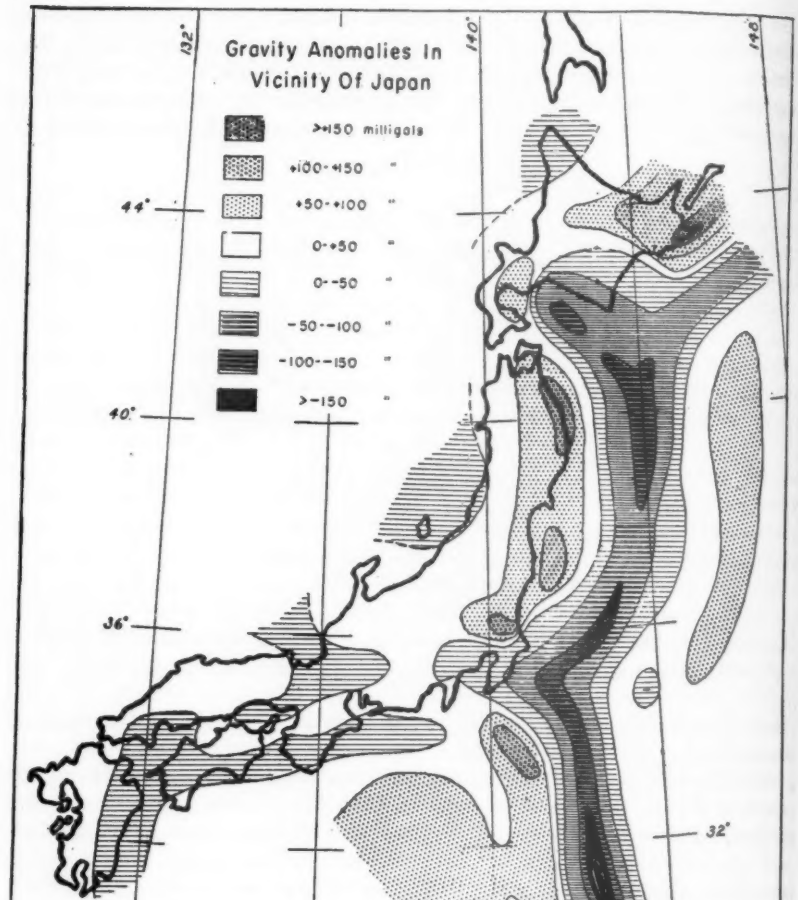


FIGURE 9.—*Gravity anomalies, Japan and vicinity*

It is similarly interrupted by the second prong but reappears to the north in Hokkaido.

Over the Bonin Trough west of the geanticline a relatively strong negative axis indicates the synclinal structure of this trough. This negative axis parallels the positive one on the Eastern geanticline. It becomes weaker to the north but apparently continues through the Fossa Magna on Honshu. West of the negative axis

a second positive axis appears over the Western geanticline. It is weaker and less well defined than is the first positive axis and it dies out before reaching Japan.

Probably these positive and negative axes continue southward at least to the southern end of the Marianas in conformity with the topographic extensions. In the small arcs of the West Carolines and Palaus a few observations by Vening Meinesz indicate analogous structures but on a smaller scale. The anomalies are not so large, and the positive and negative axes are closer together. The arcs are not only smaller and of smaller radius of curvature, but the geanticlines are much closer to the trenches. This suggests that a thinner crust may be involved in the deformation at the southern termination of the series of arcs.

THE PATTERN OF ISLAND ARCS

Probably the most evident feature of island arcs and the simplest to observe is their curved pattern on the Earth's surface. The regularity of the curvature and the fact that many arcs correspond closely to *small* circles on the globe led Lake (1931) to suggest the interesting though probably untenable idea that they represented the intersection of low-dipping thrust planes and the spherical surface. In the Aleutians Murray (1945, Fig. 1) has demonstrated that this arc corresponds almost exactly to a small circle of radius 760 statute miles through an angular distance of 125°. The Kurile arc likewise forms a small circle but of somewhat larger radius.

The Marianas illustrate nicely such an arc. The axis of the outer trench has a curvature approximating fairly well, for most of its length, a small circle of 660 km. radius through an angle of 130°. The island arc has a slightly smaller radius of curvature through a distance of 90°. The center of this circle is about 180 km west of the center for the trench. The Western geanticline has a much larger radius of curvature, 900 km through an arc of 65°, and its center lies 500 km farther west. The smaller West Caroline and Palau arcs have radii about half that of the Marianas, and the Ryukyu arc has a radius about 100 km larger than the Marianas. In contrast to the above, the arc from the Marianas to Japan and the arc of the Eastern Philippines do not seem to form small circle curves.

Looking at a more complex arc, the East Indies, a long gentle curve such as that through the Andamans, Sumatra, Java, and the Sundas suddenly increases in curvature to form the Banda arc and then doubles back on itself between Celebes and Halmahera.

The outstanding fact is the smooth curvature of the individual arcs whether radii be constant or not. This undoubtedly means something in terms of their structure and the mechanics of their formation. One is tempted to compare them to the transverse curving lines across a flowing glacier or the shapes formed by tar moving down a gentle slope. The shapes in other words suggest forms developed by plastic or pseudo-viscous flow.

GENERAL SUMMARY AND CONCLUSIONS

The geological information for most of the area considered is scanty. The writer has made the best guesses he could from the available literature (much of the Japanese literature is unavailable), from scattered personal observations in the field,

and from discussion with various members of the U. S. Geological Survey who had been in Japan or on the islands since the end of the war. There is much conflicting information on the ages of the two major deformations. The writer had dated one of these tentatively as Mid-Mesozoic and the other as late Cretaceous to early Eocene. There is, of course, considerable deformation within the Tertiary. The writer believes that the significant fact is the time of initiation of each great deformation and not the subsequent pulses of deformation along the same zone even though they may be severe.

Since it was thought desirable to distribute the chart and accompanying paper at the earliest possible date, only a few months consideration was given to the preparation of this manuscript. If it had been possible to give several years thought to the problems presented by this large and complex area, a much more refined piece of research could have resulted. The present paper is merely a rapid reconnaissance of the situation. It is hoped that by presenting it at this time, others still in the area may be assisted in carrying the research forward.

The main conclusions relating to geological structure are:

(1) The junction between arcs as indicated by topography is sharp, approximately at right angles. Gravity data over the junction of the Kurile, Japanese, and Nanpo Shoto trends also indicates the angular nature of the junctions. The alternative, that the arcs are linked together by "S" curves, does not seem to be true.

(2) The deep trenches reveal the major structural feature of the area, the zone of downbuckling of the crust, or tectogene. The existence of this structure is proven by the gravity anomalies. Most of the other major structural features are related to the development of the tectogene and are in this sense subordinate to it.

(3) Geanticlinal ridges indicated by the bottom topography parallel the inner concave side of the tectogene. The strong positive gravity anomalies over the Bonin and Iwo Jima geanticlines indicate that they represent major upwarpings of the crust. Volcanic activity is common on the crests or back slopes (western slopes) of the geanticlines, but it is believed that the volcanics merely form a veneer on the top of a structural ridge and not that the ridges are essentially piles of volcanic accumulations.

(4) An older island arc trend now mostly uplifted to form large land areas follows the Japanese islands, Nansei Shoto, Formosa, and the Western Philippines. Study of the structure of Kyushu and southern Honshu should reveal by analogy the nature of the structures over the downbuckled zone in such younger arcs as the Bonins and Marianas.

(5) The Andesite Line is defined as running along the outer (eastern) margin of the trenches, dividing the region of island-arc structure from the Pacific basin in which the volcanism is dominantly basaltic. It is a structural, petrological, and physiographic boundary. There is no discernible deformation of the ocean floor on the Pacific Basin side of the trenches, indicating that all the activity is coming from the concave (western) side of the arcs.

(6) Shallow earthquakes are concentrated over the tectogene, and moderate-depth activity is concentrated along a plane extending inward and downward at about 45° from the base of the tectogene. Deep-focus earthquakes normally follow the

trend of the tectogene at a position also inward and 45° downward from its base, but significantly depart from this position in some cases.

(7) Peridotites parallel the tectogene axis at a distance of about 50 miles as in other island arcs. Few are exposed in the younger island arc system since the uplift, and depth of present erosion has in general not been sufficient to cut through the cover of younger volcanics. They are, however, common along the older, more deeply eroded belt of deformation and were here used for tracing the extent of and dating that deformation.

(8) The Caroline Swell and Basins subdivision is considered an oceanic area resembling the South Atlantic.

(9) Great differences are noted in the stage of structural development of arcs initiated at the same time. The northern New Guinea mountain ranges represent a late stage in which seismic and volcanic activity have ceased and the arc has risen to form high mountains whereas the Marianas remain in an island-arc stage little different from when they were first formed near the end of the Cretaceous. Small portions of the older belt of deformation such as the Nansei Shoto are still in a youthful island-arc stage of development though most of that belt rose long ago into a mountain system and has subsequently been eroded to more moderate relief.

(10) Recognizable fault scarps on the ocean floor are remarkably rare. Only three are recognized within the area of the chart. It is postulated that these are transcurrent faults. A great fault zone transsecting the Philippine Islands is also considered transcurrent.

(11) The Fossa Magna depression extending north-south through Honshu is considered a structural analogue of the Bonin Trough farther south.

(12) The small West Caroline and Palau arcs may represent an area where the upper crust is abnormally thin since the gravity anomalies are smaller than elsewhere along the series of arcs which have been examined and the distances from the trench axes to the geanticlinal axes are much smaller too.

(13) The smooth curving pattern of island arcs on the earth's surface can perhaps be accounted for if the pattern were initiated by subcrustal flow.

This paper is largely a descriptive one to accompany the bathymetric chart. The conclusions and deductions made follow closely the observed and inferred structural and geological relationships. Highly speculative relationships such as those bearing on convection currents within the Earth and their possible connection with the formation of the arcs will be treated separately in a later paper. Since the speculative material is bound to be controversial, it is hoped that separate presentation will limit controversy to the speculation without impairing the descriptive portion.

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TIME-STRATIGRAPHIC CLASSIFICATION OF SEDIMENTARY ROCKS

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ABSTRACT

There are many kinds of stratigraphic units—rock-stratigraphic units, bio-stratigraphic units, and stratigraphic units based on mineral character, electrical character, seismic properties, environment of deposition, etc. *None* of these are intrinsically *time*-stratigraphic units though each may have time significance to a lesser or greater degree. Radioactivity may eventually furnish a method for truly measuring time in sedimentary rocks, but at present paleontologic (bio-stratigraphic) evidence is the most useful means we have. It should be recognized, however, that paleontologic evidence of time in rocks is *always imperfect*, that it may in certain cases be exceeded in value by other types of stratigraphic evidence, and that true time-stratigraphic units exist for us only as the ideal *concepts* of material stratigraphic units comprising the rocks formed during a given time interval, bounded only by time surfaces and independent of lithologic, paleontologic, or other facies.

Because of the more or less orderly evolutionary sequence of life forms, the present large-scale geochronologic time-stratigraphic divisions (*systems* and *series*) can generally be recognized paleontologically with rough accuracy throughout the world, although it is doubtful that their division points are marked by "natural breaks" in the fossil record. However, it is useful and desirable to apply the time-stratigraphic concept also to units of lesser rank where the purpose is perhaps not so much *geochronology* as the mere determination of *synchrony*. In the case of these smaller units (*stages*) we are approaching a limit to the degree of resolution possible in the use of evolutionary sequence of fossils, and at this scale the percentage error in the carrying of time-stratigraphic divisions by means of fossils has increased so much that this method is not infrequently exceeded in value by evidence from other stratigraphic features—lithology, mineralogy, electrical character, chemical composition, relation to diastrophism, relation to climate, etc. Since the application of time-

stratigraphic concepts to the sediments of brief time spans is nevertheless extremely useful and important to us, we are justified in employing any or all available lines of evidence for dividing and extending such minor time-stratigraphic units and we should not restrict criteria to any one group of fossils or any one facies of fossils, nor yet to fossils in general.

Even when the bases for stage divisions are restricted to fossils, we inevitably have an overlap of these units when considered on a world-wide or even a regional scale, since we cannot reasonably expect correspondence between time lines in one area based on one group or one facies of fossils and those of another area based on other groups or other facies of fossils or those of a third area with no fossils at all. Since we thus already have overlapping stages, there is no objection to the use of other than paleontologic bases for stage division on the grounds that this would result in overlapping time-stratigraphic divisions. On the contrary it would seem to be a healthy procedure to allow initial minor time-stratigraphic units to be based on any feature characterizing any well-defined part of a sedimentary section whose time equivalent it might be useful to recognize (either practically or theoretically) in another section, regardless of whether the feature were paleontologic, lithologic, mineralogic, or of still different type. Obviously the number of stages should desirably be maintained at a minimum compatible with maximum service to stratigraphy. However, if stages are adequately defined and correctly used as purely time-stratigraphic units, it does not so much matter how many are made or on what they are based—only those which are of service will survive.

Although all of the useful minor time-stratigraphic units would not necessarily have *chronologic* time significance there should be nothing to prevent the eventual establishment of definite chronologic Stages forming aliquot parts of the standard Series if, as, and when adequate bases for them are found. Since it has been proposed that the terms System and Series be capitalized when used in a geochronologic sense, the formal geochronologic Stage might be conveniently distinguished by a capital S from the stage used merely in the sense of any minor time-stratigraphic unit.

INTRODUCTION

The classification of natural processes and the results of natural processes into an orderly system of named units and subdivisions is commonly applauded as an essential and logical part of man's scientific approach to Nature. At the same time, it should be remembered that it is also frequently a measure of the inadequacy of man's mind to fully grasp and deal with natural phenomena. His need to apply an arbitrary and strictly delimited classificatory system to what in Nature is frequently a continuous process or gradual change in characters results from the clamoring of the human mind for steps on which to rest as a relief from the more precarious footing of the continuous slope which often more correctly represents these natural relations. Our methods of approach to natural problems are frequently comparable, in their oversimplifications and ultimate error, to the methods of arithmetic as contrasted with those of calculus—to determination of the area under a curve by dividing it empirically into unit blocks and adding these together rather than finding the correct integral and solving for dx.

Much of our scientific progress has indeed been accomplished through the methodical division and segregation of natural features according to degree of relationship, and we have no intention of minimizing the contribution of classifications and groupings to our understanding of Nature. However, we do wish to emphasize the danger

of our eventually coming (through repeated usage, wishful thinking, and the hypnotic power of verbal labels) to accept divisions which have been brought in through expedience as "natural" and therefore sacred units and to let them control rather than aid our thinking.

No one can deny the usefulness to the paleontologist of the taxonomic terms *order, family, genus,* etc.; yet it is healthy to remind ourselves that genera are artificial groups, that they are unknown to Nature itself, that they are man-made and as imperfect as the state of man's knowledge and the limited capacity of the particular man who made them. Every day we see differences in usage from one person to another, and needs for revision of the original concepts, and in general we find that the more we know about any particular group of organisms the less sharp become the distinctions between our genera.[1]

Likewise, in the early stages of our introduction to geology we classify rocks with assurance as sandstones, limestones, claystones, etc.; but with further experience we find all degrees of intergradation along an infinite number of lines, and we realize how arbitrary must be our pigeonholing and classification into any limited number of named units. Still more complex becomes our problem and still more arbitrary our divisions when we come to classify the sediments of the earth into the larger rock-stratigraphic units such as formations, members, groups, etc. We have built up an immense number of named formational units throughout the sediment-covered portions of the earth's crust and we need these names for the sake of intelligent intercommunication of thought, just as we need the words of spoken or written language in order to pass ideas from one individual to another. In both cases, the finer the shades of thought we wish to express, the greater the vocabulary which is necessary. On the written page our formational units sound fairly definite yet almost invariably when we come to examine them in the field, when more and more information becomes available about them from detailed outcrop studies, from well sections, from geophysical studies, we find our clear-cut divisions fading away in the intricacies of facies gradation, development of diastems and unconformities, degrees of secondary alteration, or complex intertonguing of units. We find equally qualified workers making quite different divisions, because of varying emphasis on different formational characters; and we find perpetual revision and modification of earlier definitions. Nature did not always make sharply defined rock-stratigraphic units, and any attempt to strain the delineation of such units beyond their innate gradational character is not scientific progress.

PURPOSE AND ACKNOWLEDGMENTS

Recently a statement on *Nature and classes of stratigraphic units* has been submitted to the American Commission on Stratigraphic Nomenclature by Dr. R. C.

[1] *Compare* D'Archiac (Paleontologie Stratigraphique, pp. 126–127, 1864): "Les classifications ne sont que des moyens créés pour suppléer à l'insuffisance de nos facultés, lesquelles ne nous permettent pas de saisir à la fois les rapports des divers éléments d'une science, de tout comprendre ni de tout retenir. Ainsi une classification est toujours quelque chose de plus ou moins artificiel; ce que l'on appelle *classe, ordre, famille, genre,* ne peut être consideré que comme abstractions de notre esprit, plus ou moins en rapport avec les objets destinés à aider la mémoire. Il n'y a point de classification dans la nature ou tout est si parfaitement ordonné. Ce n'est, en resumé, qu'un instrument de mnemonique d'autant plus parfait que l'exprime mieux les affinités naturelles des objets auxquels on l'applique et que ceux-ci ont un plus grand nombre de rapports communs."

Moore (1947), chairman of this commission. Expressions of opinion on this subject have been invited. The following discussion outlines the writer's views on certain phases of stratigraphic classification with particular reference to time-rock units of the lowest order (stages and substages). It draws freely from previous published statements by the writer, (1937; 1941; *see also* Schenck *et al.*, 1936) repeating and amplifying them where further emphasis is deemed desirable or where the original meaning appears not to have been clear. It comments on those few specific points in Moore's admirable statement which appear questionable to the writer. For comments pro and con on points in the manuscript draft the writer is particularly grateful to M. N. Bramlette, John Bartram, Marshall Kay, R. C. Moore, Georges Pardo, Augustin Pyre, J. B. Reeside, W. W. Rubey, Amos Salvador, George Gaylord Simpson, and Chester Stock.

CLASSES OF STRATIGRAPHIC UNITS

Stratigraphy is that branch of geology which treats of the character (lithologic, paleontologic, mineralogic, etc.) of the earth's sedimentary strata, their chronologic sequence and time relations, their lateral and vertical variations and subdivisions, and their conditions of origin. There are naturally many types of stratigraphic units. The earth's strata may be classified according to lithologic and lithogenetic character into rock-stratigraphic units: formations, members, groups, tongues, lentils, etc. They may be classified according to fossil content into bio-stratigraphic units: bio-zones, fauni-zones, zonules, etc. They may be classified mineralogically into mineral zones. They may be classified on a purely environmental basis into marine deposits, terrestrial deposits, deltaic deposits, etc. They may be classified on the basis of velocity of transmission of seismic waves, on electrical resistivity, on chemical character, and in many other ways.

TIME-STRATIGRAPHIC CLASSIFICATION

Of particular importance in stratigraphy is the classification of strata with respect to geologic time. Time-stratigraphic classification organizes the earth's strata into units of greater or lesser rank representing the material deposits of specific time spans in the earth's history regardless of lithology, fossil content, or any other characters. Such units are the system, series, stage, etc. Parallel to these time-stratigraphic units and dependent on them for definition are equivalent *time* units: period, epoch, age, etc. These last are not material units and are not in themselves stratigraphic units although based on time-stratigraphic units.[2] Serious confusion has frequently arisen in stratigraphic work through the careless usage of rock-stratigraphic and bio-stratigraphic terms as time-stratigraphic terms and the use of time-stratigraphic units as time units.

[2] That time units should not be considered to be stratigraphic units is apparent from the original definition of the word *stratigraphy* which fundamentally involves the *material* bodies known as strata. The distinction between time and time-stratigraphic units is brought out by the fact that, while certain time-stratigraphic units may be missing in certain areas either due to nondeposition or erosion, their corresponding *time* units were just as real and existent in these areas as elsewhere.

The purpose of time-stratigraphic classification is not only to provide "a framework that may serve adequately as foundation for accurate and complete recording of successive conditions and events in geologic history" (Moore, 1947, p. 521) but also simply to express synchrony (or lack of synchrony) of sediments from one area to another or one section to another, regardless of a system of world-wide geological chronology.[3] The degree of success with which time-stratigraphic classification can be accomplished depends fundamentally on the extent to which nature has left in the sediments indications of their absolute or relative time period of deposition. The simple feature of physical superposition of strata provides a fundamental relation of rocks to time but is only of local application because of the lack of lateral continuity of strata, the transection of time lines by lithology and bedding planes, and the barriers to extended lithologic correlation. Nevertheless, it is one of the most direct and effective methods; and improvements in the technique of tracing strata, particularly in well bores, have greatly increased its area of application.

Fossils, of course, constitute one of the best means of both correlating and dating rocks; because of the more or less orderly evolutionary sequence of life forms on the earth (worked out, however, only through relation of fossil occurrences to the succession and superposition of strata), they constitute by far the most effective means of setting up a *chronological* system of time-stratigraphic divisions. However, there are limits to the resolving power of fossils as chronological indicators. While sediments differing in age by 20 million years, for example, may be readily placed in their correct sequence by an experienced paleontologist, smaller differences in time become progressively more difficult to place correctly, and a limit is finally reached where facies variations and other factors completely mask the changes in fossil record due to difference in age.

Numerous other features besides order of superposition and paleontology can contribute evidence of relative age. Among these are radioactive measurements, relations to diastrophic events, evidences of volcanic activity, climatic changes, unconformities, sedimentary cycles, transgressions and regressions, etc. Many of these may, in special cases, become of outstanding importance and exceed in value all other means. However, only fossils (and perhaps radioactive measurements)[4] are of much service in determining complete and world-wide *geochronological* sequences. The others, such as diastrophic periods for example, may serve to divide the story into volumes, chapters, and pages, but fail to place numbers on these units to show their sequence.

DEVELOPMENT AND SIGNIFICANCE OF MAJOR TIME-STRATIGRAPHIC UNITS

In seeking better to grasp the history of the earth, sedimentary strata were divided during the nineteenth century into *systems*, paralleled by a geochronologic sequence

[3] The writer differentiates between *synchrony*—the expression of time equivalence or contemporaneity—and *chronology*—the expression of order, sequence, or position with respect to time.

[4] That radioactive measurements may eventually have greatly increased applicability to the dating of sediments is suggested by recently reported progress in the use of ionium and carbon isotopes in the age determination of relatively recent sediments and in the use of strontium isotope ratios in connection with the dating of ancient sediments and particularly of fossil shells themselves.

of time *periods*. The periods were grouped into four or five *eras* and have been subdivided into *epochs* to correspond to the division of the systems into *series*. These divisions were largely made in Europe, while the science of stratigraphy was in its infancy, and when the stratigraphic sequences of only a very small portion of the earth's crust were known. Many of the systems were originally based on lithologic features thought to characterize the rocks of a particular age (Carboniferous—coal measures; Cretaceous—chalk); others were developed simply to include the sedimentary rocks of certain geographical localities; still others were worked in as compromises to include intermediate disputed strata. In general the bases for definition of the original systems were remarkably varied and haphazard, and their order of establishment was without any relation to their position in the time scale and with little relation to any organized plan for geochronologic subdivision of the earth's strata as a whole. Most of the systems in their locality of origin could be distinguished readily from adjacent ones by differences in fossil content, and their authors believed them to be indicative of natural division points in the earth's history marked by abrupt and extensive changes in life forms. Perhaps even more than the originators themselves, their immediate successors assumed these units to be distinct "steps" in a time-stratigraphic scale which would be found continuous over the whole earth.

Later work has shown that most of the supposedly sharp breaks in the fossil record were actually due to changes of facies or to unconformities or hiatuses which left gaps in the local sequence of strata. Sedimentary sections have now been found elsewhere in the world filling in those gaps between the units as originally defined in Europe and completing a more orderly and continuous sequence of fossils than was originally believed to exist. However, under the weight of early ideas the belief has persisted that these time and time-stratigraphic divisions are "natural" units, marked off by distinctive world-wide events and abrupt changes in the evolutionary sequence of life forms. Now, throughout the history of the earth, organic evolution, when looked at as a whole, has taken place very gradually. There have been accelerations and retardations in individual groups, but considering *all* types of organisms there is little basis for localizing time divisions to particular points in the earth's history on the grounds that they coincide with particularly marked changes in life forms. It is perhaps true that the boundaries of many of the standard time-stratigraphic divisions coincide closely with the times of extinction of certain groups, or times of accelerated evolution of other groups. Still other forms, however, would show their greatest changes in the midst of these time-stratigraphic divisions. To relate our present time-stratigraphic boundaries to evolutionary changes requires the selection of certain types of organisms to the exclusion of others which would have suggested the placing of boundaries at quite different points in the time scale. "Natural" boundaries based on general life evolution must be rare, and specialists in each particular group of organisms would set up quite different classifications, if the strata of the earth were to be divided in accordance with the development of their own particular group. To doubt that "natural breaks" delimit our present systems and series, it is only necessary to examine the controversies which have arisen between

specialists over almost every one of these boundaries, and to note the lack of agreement which still remains, depending on the type of fossils used as indicators.[5]

Through the advantage of an early start and the authority of their founders, the originally named European systems and series became in large part accepted as standards, and succeeding generations of enthusiastic stratigraphers have with more or less success forcibly fitted the strata of the rest of the world into this same mold, in spite of the fact that had the initial stratigraphic divisions been made in another continent a quite different classification would no doubt have resulted. However, since these established systems and series represent relatively large time-stratigraphic divisions they can be recognized quite readily in a general way throughout the world on the basis of the approximate stage of evolution represented by their fossils, and it is usually only at their boundaries that doubts and uncertainties in identification exist. As previously discussed, we must have subdivisions of the earth's history and stratigraphy in order to facilitate grasping, discussing, and handling these concepts. In spite of the admittedly arbitrary and chance nature of many of the boundaries in our present scheme of classification, these major units can be carried with considerable assurance from continent to continent, their relative chronological position is quite definite, and all in all they have proved quite useful and satisfactory world-wide time-stratigraphic units.

MINOR TIME-STRATIGRAPHIC UNITS—STAGES

The importance, in both economic and purely scientific work, of relating rocks to time makes it highly desirable and of great utility to employ also time-stratigraphic divisions of smaller scale than systems or series. The term *stage*[6] was developed in Europe during the last century as a time-stratigraphic term subordinate to a series. The European stages were originally based largely on lithology and on cycles of sedimentation. It was found later that each lithologic stage had its characteristic fossil content, and stages were then extended to adjoining areas largely on the basis of their fossils (Gignoux, 1936). As in the case of the larger units, the boundaries of the original stages have frequently turned out to be marked by unconformities or changes in facies. Consequently when the missing strata, or succeeding strata of

[5] The absence of natural boundaries between the rocks representative of geologic eras as well as between many of the systems has been emphasized by R. H. Rastall (1944). Referring to the section above the pre-Cambrian in Britain and parts of America Rastall says "It is this long and almost unbroken succession that gave rise to the greatest difficulties of the stratigrapher: it was unwieldy and he wanted to split it up and make pigeon-holes, whereas Nature worked more or less continuously, the breaks patent in one area being commonly bridged over in another."

[6] *Stage* is, of course, the English translation of the common French word *étage* meaning "layer", "step", "degree", "floor". Consequently its first use is probably as old as stratigraphy itself. In Volume I of the Bulletin of the Societé Géologique de France (vol. I, page 217, 1831) the term was used by Omalius d'Halloy who gives it rank in the fourth order of stratigraphic terms—higher that his "systeme" and lower than his "terrain". D'Halloy does not propose the term as new. D'Orbigny, to whom the origin of the term stage is frequently attributed, used it throughout his *Paleontologie Française* (1842–1849) as a means of escaping from local lithologic or paleontologic terms. Stage divisions were based on "an annihilation of an assemblage of life-forms and its replacement by another." To D'Orbigny the stage as a stratigraphic term represented the deposits of a certain geological epoch or period "demarcated as well by the different faunas they contain as by stratigraphical boundaries". He conceived the stage divisions as world-wide—as everywhere natural, not arbitrary. In his *Paleontologie et Géologie* (1849–1851) he divides his stratigraphic column into stages and discusses at some length the criteria for the division of stages. His concept is not quite clear, however, as in some cases "étage" is used by him as an interval of time and in other cases as the rocks deposited during that interval. Moreover, while D'Orbigny considered the Silurian, Devonian, and Carboniferous as stages, he also placed minor divisions of the Cretaceous and Tertiary in an equal rank.

the same facies, were studied elsewhere much of the abruptly distinctive fossil character of each stage was found to disappear. Stages have generally been limited in extent to individual regions, and a complete world-wide system of stages has not been set up. In fact, in many regions stage divisions have not been recognized at all. However, there has recently been a distinct and highly commendable tendency toward the expression of time-stratigraphic concepts on a smaller scale than systems and series, and it is important to agree on the bases for subdivision and the terms to be used for these minor units.

We have seen that in larger time-stratigraphic units, even though boundaries between them may be very arbitrary, it is still possible to relate them to the world-wide sequence of organic evolution. They thus have fairly distinct *chronologic* significance. However, in smaller divisions (stages and substages) determination of relative chronologic position through relation of contained fossils to the general evolutionary sequence becomes increasingly more difficult, since the same means must be used as for systems and series, only refined to a much greater degree. If the division lines between systems and series, as related to evolutionary sequences, are arbitrary, those between stages must certainly be far more so. On this small scale, evolutionary differences in life forms are frequently masked by facies differences, and periods of change in one type of organism are not paralleled by those in other types of organisms. In other words, there is inevitably a limit to the degree of resolution possible in the use of the evolutionary sequence of fossils as a key to chronology; and in time-stratigraphic units of lesser rank than series (stages and substages) we are closely approaching or perhaps even passing this limit. Stages have just as fundamental and intrinsic *time* significance as the larger units, but their *chronologic* significance is less. Yet the innate human fascination for orderly classification still strains toward fitting them into the same scheme of chronologic world-wide time-rock divisions as the larger series and systems.

As we have said, the purpose of time-stratigraphic units in general is not only to build up a sequence through which the sediments and history of the earth can be related to the passage of time. It is also simply to provide a mechanism by which the deposits of one section or one area may be compared to those of another on the basis of time. Geochronology is not the only goal of time-stratigraphic classification. Mere synchrony and correlation are also important, and small-scale time-stratigraphic units are extremely useful regardless of whether they fit into our geochronologic classification based on life evolution.

BASES FOR ESTABLISHMENT AND GEOGRAPHIC EXTENSION OF STAGES

The *concept* of the ideal time-stratigraphic unit—that of a material body of strata comprising the sediments deposited during a given time interval, bounded only by time surfaces and independent of lithologic, paleontologic, or other facies—is of paramount importance to us. No means available at the present time for extending time-stratigraphic units from one area to another is perfect. However, since time-stratigraphic units and concepts are extremely useful to us we are justified in employing any or all available lines of evidence for extending these units and concepts

as well as possible, and we should not restrict criteria to any one group of fossils or any one facies of fossils nor yet to fossils as a whole. It is just as important to use time-stratigraphic units and concepts in connection with non-fossiliferous strata as with fossil-bearing beds, and it is important to use them with fossiliferous strata of many different facies and where fossils may be exclusively plants, or land vertebrates, or fishes, as well as where they are mollusks, foraminifers, or trilobites. In short, *it is desirable to be able to express as a time-stratigraphic unit the sediments equivalent in age to the time scope of any recognizable feature of sedimentary rocks which may be useful as a stratigraphic measuring stick*—the time range of a certain species of gastropod, of an assemblage of foraminifera, of a sequence of plant fossils, of a certain lithology, of a specific mineral assemblage, of a certain chemical composition, etc. The important point is that the basis be adequately defined and that, in the ideal, the time-stratigraphic unit be extended from its type locality purely by means of time lines and independent of lithology, paleontology, mineralogy, or other features.

It is, of course, a commonplace of stratigraphy that lithologic units (formations, members, etc.) may cut across time lines, and it is generally recognized that lithologic boundaries are quite widely independent of time. The same applies, however, in greater or less degree to units based on any other features of sediments. We have numerous types of stratigraphic units (lithologic formations, mineral zones, paleontological zones, etc.), but *none* of these are intrinsically *time*-stratigraphic units. Paleontologic features are at present the most useful means we have for extending time-stratigraphic surfaces, but even they are *always imperfect*. The first specimen of any newly developed species is bound to be older than any other specimen, and the first occurrence in one area is never exactly of the same age as the first occurrence in another area. New life forms did not spread instantaneously, nor were old forms extinguished everywhere at the same moment. Moreover, the *percentage* error in the carrying of time-stratigraphic divisions by means of fossils increases as the size of the unit diminishes so that at the scale of *stages* or smaller divisions the accuracy of fossils as a means of reconstructing time-stratigraphic horizons is not infrequently exceeded in value by other types of evidence. Thus locally a lignite bed or a volcanic ash may furnish a much more accurate time horizon marker than the associated fossils, and on occasion time-correlation of strata may be carried out with complete independence from fossils, through relation to underlying or overlying beds, to vulcanism or diastrophic events, to lithology, mineralogy, electrical character, chemical composition, etc.

RELATION OF BIO-STRATIGRAPHIC UNITS TO STAGES

Some paleontologists would insist that the criteria for stage division be fossils and that stage divisions should be placed only at "natural breaks" in the evolutionary stratigraphic succession of fossils. However, there is considerable reason to doubt man's ability to pick, at the scale of stage divisions, "natural breaks" which would indicate consistent time horizons over any considerable area. Abrupt and well-marked biostratigraphic changes of this order in any section are more likely to be due to changes of facies or interruptions of deposition and thus are not of special geo-

chronologic significance as time-rock divisions. If, for example, the various facies of shallow-water marine environments with their abrupt faunal changes were traced seaward to areas where deposition had been essentially continuous in a stable environment and at a constant rate, it is doubtful if any special division points could be recognized. However, *if* regional "natural breaks" in the evolutionary sequence of life forms can be found that define units of the scale of subdivisions of a series, these indeed make desirable stage divisions and have not only simple correlative value but also geochronologic value. Such stages are comparable to those set up on the basis of Foraminifera by Kleinpell and Schenck in California. If their limits do not coincide with those of other already established stratigraphic divisions, it is highly desirable and useful to give them new and independent names. Here again, however, it is essential that a type section be adequately defined and that the unit be extended strictly as a time-rock unit.

Assuming (for the sake of discussion only) that stage divisions should be based exclusively on fossil evidence and that "natural breaks" of this order of magnitude do exist and can be recognized, then it is still not clear to which group of fossils preference is to be given in making these divisions. Presumably, specialists in the Foraminifera would base their stage divisions on Foraminifera, vertebrate paleontologists on vertebrates, paleobotanists on plants, and so on. Moreover, it is certainly conceivable that in a single region, depending on local facies, a useful system of time-stratigraphic divisions might be set up in one place based on vertebrate fossils, in another based on Foraminifera, in another on fossil plants, and in another on mollusks. Each might be very useful in correlation, but it would be very amazing indeed if the units of each system had the same natural boundaries—and as long as each was useful there should be no need for trying to force them into a common mold or of suppressing the mollusk-based stages (for example) in favor of the vertebrate-based stages, merely because the latter may have had priority. There could easily be as many different "natural" systems of stage divisions as there are groups of fossils. This is not an unacceptable condition, but certainly there is then no point in confining stage divisions to paleontology as a means of insuring a simple single system of geochronologic stages.

Finally, it must be emphasized that the distribution of fossils in sedimentary rocks is controlled by depositional facies just as is the distribution of lithologic types. Points of appearance and disappearance of species or groups of species may, on account of facies changes, be no more indicative of time horizons than are lithologic boundaries. Although a thread of evolutionary change runs through the fossil content of the earth's sediments, which makes it particularly useful for major geochronological divisions, the smaller the units which are under consideration the more predominant become facies changes and the less discernible the evolutionary changes. The time value of stratigraphic units based on fossils will fluctuate from place to place with faunal-facies variation in much the same manner as the time value of a lithologic formation may vary. Certainly bio-stratigraphic units are not necessarily time-stratigraphic units, and a clear distinction should be made between them just

as the distinction should be made between rock-stratigraphic units and time-stratigraphic units.[7]

"The principal unit in the bio-stratigraphic category is the *fauni-zone*[8] which has been defined as a bed or group of beds characterized by an assemblage of organisms, one of which is chosen as index species (or index genus) and gives its name to the unit although it need not be confined to this unit or found in every part of it. A companion term is the *bio-zone*, which is constituted by the strata deposited during the life duration of any particular species. Bio-stratigraphic divisions (as also rock-stratigraphic divisions) may serve as the bases for time-stratigraphic units but strictly in themselves they are not time-stratigraphic divisions. The time-value of fauni-zones may fluctuate from place to place with faunal facies variation in much the same manner as the time value of a formation and the time value of a bio-zone may vary with the area or region under consideration. Moreover, a zone (bio-zone or fauni-zone) may be extended appropriately only to the limits of the occurrence of the characteristic species or assemblage of forms on which it is based, regardless of the continuance laterally of sediments of the same age but with different fossil content. Obviously any number of fauni-zones and bio-zones may be established with any number of overlapping time values depending on the group of fossils under consideration and the species chosen within this group. Only rarely will there be a sufficient concentration of individual bio-zone limits throughout all groups of organisms at any particular time horizon to allow anything but a rather arbitrary choice of bio-zones to be used as a basis for time-stratigraphic divisions of lesser than series rank" (Hedberg, 1941, p. 2206). Moreover, the bio-zone limits in any one section (Teil-zone) may be quite different from the scope of the bio-zone for the region as a whole.

RELATION OF ROCK-STRATIGRAPHIC UNITS TO STAGES

It is frequently useful to be able to refer to the sediments equivalent in age to a certain formation or rock unit. Naturally the formation as an abstract rock-stratigraphic term has no direct time significance. It is a lithologic or lithogenetic unit; its deposition may represent a long or a short time interval; and in its total extent its boundaries may cross and recross time horizons. However, any specific formation has a time value—the time interval from the moment its deposition started to the moment it ceased. The sediments deposited during the time interval represented by the Austin chalk, for example, might be considered as belonging to the Austin stage, regardless of lateral lithologic gradation into differently named formational units. In this connection, distinction should be made between the Austin stage (the sediments represented by the interval required for the deposition of the Austin chalk as a whole) and the *type* Austin stage (the sediments deposited during the time interval represented by the defined type section of the Austin chalk). The same distinction must, of course, be made in the case of any biostratigraphic unit also.

[7] Excellent discussion of the limitations of fossils in correlation and age determination have recently appeared (Kay, 1947; Spieker, 1946.

[8] For discussion of this and other zone terms *see* Arkell, 1933.

Formations are fundamental, and familiar stratigraphic units with which we deal every day in stratigraphic work and their limits are much more readily ascertainable than are those of paleontologic units. It is obviously of great utility to be able to refer to one section in terms of general time equivalence to formations or other rock-stratigraphic units of another section. (In petroleum geology, particularly, ascertainment of the time equivalence of the lithologic units of one section to those of other sections is one of the principal objects of stratigraphic work.) Moreover, as mentioned above, it not infrequently happens that certain lithologic features, reflecting climatic conditions or composition of sea waters for example, have as much or more time significance with respect to the sediments of a region than do the fossils which these sediments contain. They consequently have equal or greater value for time-stratigraphic divisions than do the fossils. Also it may frequently be desirable and feasible to use time-stratigraphic subdivisions in series which are essentially non-fossiliferous throughout a whole region either because of facies or because of age (pre-Cambrian). A volcanic ash bed, a coal bed, a glacial till, or varved clays may conceivably constitute much more accurate time markers throughout a region than the best fossil division which can be made. It is therefore hardly reasonable to restrict the criteria for stage division to paleontology and it may frequently be desirable to use lithologic formations, groups, or members as the bases for stages.

DISTINCTION BETWEEN ROCK-STRATIGRAPHIC, TIME-STRATIGRAPHIC, AND TIME TERMS

Moore's (1947) statement to the American Commission on Stratigraphic Nomenclature calls for the naming of time and time-rock (time-stratigraphic) units by means of adjectives ending in *an* or *ian*, whereas rock units are to be named by combining noun place names with the classificatory rock term. The writer does not wish to raise any particular objection to this procedure, but it is difficult to see why the *an* or *ian* form is any more necessary in this connection that 't would be to require the use of Kansas State and Kansan City or New York State and New Yorkian City. Seemingly the fundamental distinction between the different categories would be more clearly brought out by using the proper name in all cases combined with the appropriate class noun (state, city; formation, stage, epoch). Thus, if the terms epoch, stage, and formation are clearly defined, there is certainly no possibility of confusion between "Austin epoch," "Austin stage," and "Austin formation," whereas the use of the term "Austinian" alone as a substantive might indeed lead to confusion between time and time-rock concepts. Moreover, there would seem to be no more point in making a marked nomenclatorial separation between rock and time-rock terms than between time and time-rock terms. It would be much simpler and less subject to possible misinterpretation to always use the class noun *formation* when we mean formation, *stage* when we mean stage, and *epoch* when we mean epoch.

OVERLAP, NUMBER, AND MAGNITUDE OF STAGES

Misgivings have been expressed regarding the writer's suggestion that the component stages of a series might overlap and might not add up in total time value to

the total time value of the series which comprises them. Obviously, however, if we use the term stage in the broad sense of the time-stratigraphic unit corresponding to any recognizable division of the stratigraphic column within a series, the component stages will very possibly overlap, depending on the bases used for their definition and the particular time interval to which they refer. The sum of the time spans represented by all the possible stages within a series may thus conceivably greatly exceed the time span represented by the series itself. In the same way, a formation may be divided into lithologic units such as claystones, sandstones, red beds, green beds, arkosic beds, carbonaceous beds, fossiliferous beds, etc.; and due to the overlap of classifying characters the sum total thickness of all these divisions will greatly exceed the total thickness of the formation.

The dismay with which the idea of overlapping stages is sometimes received at first is probably due largely to our instinctive desire for simplicity and systematic order in our scheme of time-stratigraphic divisions. However, we know that it is already difficult in the case of the larger time-stratigraphic divisions—systems and series—to extend them over the whole world and at the same time be sure that they are maintaining their original time scope. In the case of smaller-scale divisions such as stages it is infinitely more difficult. In fact, few would pretend that the same stage divisions can be applied in widely separated areas, and it is of course well known that very different stage names and divisions are in use at the present time in different regions. The overlap of stages within a series is thus already generally accepted in the world-wide picture. However, while granting this, many would still advocate that no overlap be allowed within any one "region". What constitutes a "region" is a little uncertain. Even assuming that we confine ourselves to a single "basin of deposition" we have seen that time-stratigraphic divisions based on one type of fossils will not necessarily accord with those based on another type, that divisions based on fossils of one facies will not necessarily accord with those based on fossils of a different facies, that divisions based on fossils in general will not necessarily accord with those based on lithology, and that divisions of any sort whatsoever will not necessarily accord with those of another sort nor can they themselves be extended perfectly as time-stratigraphic horizons. We must therefore recognize a practical overlap of stages even within individual basins. Furthermore, the isolated character of many superficial basins and embayments is fast disappearing as the deep wells of modern times provide interconnecting stratigraphic sections. Future drilling development of the continental shelf areas will provide even closer ties between regions formerly considered geologically distinct, and when the stages which have been established in one region are traced into the next it will be only rarely that their boundaries will coincide. Certainly there has been no such squeamishness about overlap in Europe (the home of the stages) where the Sahelian and the Pontian are recognized as approximately time-equivalent stages representing different facies within the same region and where the Urgonian is a facies equivalent of parts of both Aptian and Barremian stages within the same Cretaceous basin of deposition.[9] True, the overlapping feature increases the complexity of stratigraphic nomenclature, but it is also more

[9] For a striking exhibit of overlapping stages in the Pliocene of the Mediterranean region *see* Gignoux (1936, p. 585).

suited to the increasing complexity of the stratigraphic ideas which we wish to express, and it allows us greater accuracy and gives a lesser incentive for forcing time-stratigraphic boundaries beyond the limits of reasonable supporting data.

The objection has been raised that the broad usage of the term stage for time-stratigraphic units corresponding to any recognizable division of the stratigraphic column comprising a series will lead to a confusing number of stages. Perhaps the same outcry was once raised about the subdivision of formations into interfingering and intergrading members, lentils, tongues, etc. However, in order to express detailed lithologic concepts it is necessary to have a detailed nomenclature and in order to express detailed time-stratigraphic concepts it is necessary to have a nomenclature to match. Certainly stratigraphic names should be kept to a minimum compatible with maximum service to stratigraphy. However, history suggests that the differential utility of the many possible time-stratigraphic divisions which can be made will itself automatically take care of this problem. Obviously, certain stages based on either bio-stratigraphic, rock-stratigraphic, or other stratigraphic units will be found more useful than others for correlation and comparison. These will gradually become established as major reference stages through their more widespread usage, in contrast to others for the scope of which there might be need only on limited occasions. It is, doubtless, in this manner that many of the principal reference stages of European stratigraphy were developed. Originally, there were numerous local lithologic units or units based on sedimentary cycles; but through fossil content or other distinguishing characters some were found particularly useful in dating strata in other areas and thus gradually took on time-stratigraphic significance. Even if the goal should be to reduce the stages in a series to a few major ones which might even constitute integral and unique divisions of the series, the freedom to use many possibilities in the early phases of stratigraphic work in a region will assure the eventual adoption of the most worthy stages much more certainly than the early and arbitrary designation of certain specific stage divisions to the exclusion of all others. Correctly and adequately define our stages and it doesn't matter how many of them we make or on what features they are based; only those which are of service will be used.

The magnitude of a stage may be left as indefinite as that of a series or system, except that stages within a certain region should be subordinate in rank to the series of that same region. It if should be desirable to use time-rock divisions of lesser rank than a stage they may be called substages. The term zone was sanctioned by the International Congress in Paris in 1900 as a subdivision of a stage, but in the interests of clarity it would seem preferable to use substage. Zone has been employed so widely and, in so many different senses, that it is desirable to qualify its use in stratigraphic terminology by a more specific prefix, as *fauni*-zone, *bio*-zone, *mineral* zone, etc.

With respect to the flexibility advocated regarding the magnitude, number, and overlapping character of stages, it should be pointed out that this same flexibility is employed without too much confusion in the subdivisions of world history of man. Depending on the particular application we wish to make, we employ any number of variously sized and overlapping time terms such as: the Christian era, the age of

Rome, the Renaissance, the reign of Louis XIV, the American colonial period, the Administration of Jefferson, the period of the French revolution, the age of electricity, etc. The most useful terms become the best established, but in specific cases and in local areas the minor terms are also useful.

GEOCHRONOLOGIC STAGES

Time-stratigraphic classification of the earth's strata into a geochronologic system of neatly packaged units of varying rank down to stages and substages, all fitting into each other evenly and completely, is indeed a beautiful dream. Perhaps it should be a goal (and there is nothing in the present recommendations to prevent the establishment or adoption of such units if, when, and as adequate basis for them can be found). But, if so, let us approach it objectively by building a firm foundation of local synchronizations which may gradually be extended to regional and world-wide units, rather than by setting up these units and then trying to fit our actual sediments into this preconceived system. Let us beware of forcing Nature into pigeon holes which she herself never knew to exist. Surely, future stratigraphers will not thank us for prematurely setting up still further rigid subdivisions of the existing scheme of chronologic stratigraphic divisions, if these prove to be based merely on fossil facies with faulty chronologic time connotation. Likewise present-day workers will be handicapped by the restriction of stage terms to units which have been defined by some particular group of fossils, to the exclusion of stage usage in non-fossiliferous strata or to the exclusion of stages based on other groups of fossils.

In the present state of our knowledge a more conservative procedure and one with greater utility would be to emphasize not so much specifically named geochronologic stages, but rather the general stage concept (that of a material stratigraphic unit comprising the sediments deposited during a given time interval, bounded only by time lines and independent of lithologic, paleontologic, and other facies) based on any recognizable divisions of a series which it may be desirable to use as a measuring stick or unit of reference. This is the stage with the little s; since it has been proposed that the terms System and Series be capitalized when used in a geochronologic sense, the formal geochronologic Stage (if, as, and when it may be established) might be distinguished conveniently by a capital S from the stage used merely in the sense of any minor time-stratigraphic unit.

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CONCEPT OF THE GRADED RIVER

BY J. HOOVER MACKIN

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ABSTRACT

Grade is a condition of equilibrium in streams as agents of transportation. The validity of the concept has been questioned, but it is indispensable in any genetic study of fluvial erosional features and deposits. This paper modifies and extends the theory of grade originally set forth by Gilbert and Davis.

A graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and the prevailing channel characteristics, just the velocity required for transportation of all of the load supplied from above. Slope usually decreases in a downvalley direction, but because discharge, channel characteristics, and load do not vary systematically along the stream, the graded profile is not a simple mathematical curve. Corrasive power and bed rock resistance to corrasion determine the slope of the ungraded profile, but have no direct influence on the graded profile. Chiefly because of a difference in rate of downvalley decrease in caliber of load, the aggrading profile differs in form from the graded profile; the aggrading profile is, and the graded profile is not, asymptotic with respect to a horizontal line passing through base level. It is critical in any analysis of stream profiles to recognize the difference in slope-controlling factors in parts of the overall profile that are (1) graded, (2) ungraded, and (3) aggrading.

A graded stream responds to a change in conditions in accordance with Le Chatelier's general law:—"if a stress is brought to bear on a system in equilibrium, a reaction occurs, displacing the equilibrium in a direction that tends to absorb the effect of the stress." Readjustment is effected primarily by appropriate modification of slope by upbuilding or downcutting, and only to a minor extent or not at all by concomitant changes in channel characteristics. Paired examples illustrate (1) the almost telegraphic rapidity with which the first phases of the reaction of a graded stream to a number of artificial changes are propagated upvalley and downvalley and, (2) the more or less complete readjustment that is effected over a period of thousands of years to analogous natural changes.

The engineer is necessarily concerned chiefly with short-term and quantitative aspects of the reaction of a graded stream to changes in control, while the attention of the geologist is usually focused on the long-term and genetic aspects of the stream's response to changes. But the basic problems are the same, and a pooling of ideas and data may enable the engineer to improve his long range planning of river control measures and permit the geologist to interpret, in quantitative terms, the deposits of ancient streams.

INTRODUCTION

The concept of grade, as a condition of equilibrium in streams as agents of transportation, has been the fundamental basis for the understanding of fluvial landforms for the last half century. The geologic literature contains, however, a number of markedly different definitions of the concept, and many geologists have been troubled by its defects and inconsistencies. An analysis of some of these difficulties leads Kesseli (1941) to conclude that the views of Gilbert (1877) and Davis (1902) regarding the equilibrium relationship are untenable and that the concept of grade must be abandoned. This article is an outgrowth of studies of stream planation surfaces in Wyoming (Mackin, 1936, 1937), was started several years before Kesseli's critique was published, and is a revision of the concept rather than a defense of the writings of Gilbert and Davis.

The engineering literature provides a counterpart for the concept of grade in the idea of the "adjusted" or "regime" condition in streams. The engineer is concerned primarily with short-term reactions of adjusted streams to damming, shortening, and deepening operations and other river training measures. The geologist sees erosional and depositional features in valleys as records of the long-term response of the graded stream to various natural changes in conditions controlling its activity. These natural changes in control are in many instances closely comparable with those introduced by man. Because they are a good test of the concept of the graded or adjusted condition, a number of paired examples of long- and short-term reactions of streams to analogous changes are brought together here; citations are drawn about equally from geologic and engineering writings.

There is much of common interest in this type of synthesis, but the geologist and the engineer differ widely in background and habits of thought, and an attempt to bridge the gap requires certain compromises in use of terms and manner of treatment. General policies are as follows:

(1) Future advances in knowledge of stream processes will certainly be based increasingly on quantitative measurement and mathematical analysis. But the quantitative aspects of transportation by running water are controversial and are not essential for an evaluation of the concept of grade; the treatment here is qualitative. If, by clarifying some of the genetic aspects of the problem in qualitative terms, or focusing attention on them, the article clears the way for more rapid quantitative advances, it will have served part of its purpose.

(2) There are two possible approaches to the study of streams as agents of transportation, (A) in terms of relationships between slope, discharge, channel form, and the size of grains comprising the load, and (B) in terms of energy transformations. Preferably, the two should not be combined. But they *are* combined in most of the papers cited, and, while the thesis of this article depends wholly on the first approach, some discussion of energy transformations is necessary. The manner in which the term energy is used is well established in the literature; it may be regarded by the specialist as loose, but he will be merely irritated rather than misled.

(3) Transporting power is considered to be a function of *velocity*, rather than the

depth-slope (tractive force) *relationship* that forms the basis for many mathematical treatments of transportation. This usage has the advantage of simplicity and, for present purposes, the differences are negligible (for analysis of these alternative theories see Rubey (1938) and discussion of Kramer (1935) by outstanding engineers, especially Matthes and Straub (p. 867–868).

(4) Partly in deference to the inveterate equation-skippers, but chiefly because critical differences between causes and effects do not appear in an equation, mathematical methods of expressing relationships are generally avoided.

ACKNOWLEDGMENTS

After the 15-year period during which the views outlined here were developed it is difficult for me to distinguish between ideas that were arrived at independently and those gleaned from reading, discussions with numerous geologists and engineers, and lectures in the classrooms of Douglas Johnson and W. M. Davis. An effort has been made to credit other workers with specific points made by them, but the 80-odd citations certainly do not cover all of the cases in which the same thoughts have been expressed before, especially in the writings of Baulig (1926), Davis (1902), Gilbert (1877, 1914), and Rubey (1933, 1938) among the geologists, and Lane (1937), Salisbury (1937), Schoklitsch (1937) and Sonderegger (1935) among the engineers. Early papers, chiefly of historic interest, are not included in the bibliography (in this connection see Baulig, 1926).

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VELOCITY AND LOAD

GENERAL STATEMENT

This section is a brief review of certain general principles of stream transportation, drawn chiefly from the works of Gilbert, Rubey and Hjulström. The principles are are based largely on laboratory studies and apply equally to graded streams and streams that are not graded. As outlined here they provide a basis for understanding observed behavior of graded streams; the concept of grade depends, not on any particular theory of transportation nor any special manner of apportioning energy losses, but on the form of the longitudinal profile developed by the debris-carrying stream under stable controlling conditions, and on profile changes that automatically readjust the stream to any change in controls.

ENERGY AND VELOCITY

The energy of a stream between any two points is proportional to the product of the mass and the total fall between the two points. This is, hereafter, the "total energy"; it increases with increase in discharge or slope but is increased also, negligibly for present purposes, by the presence of debris in motion in the water.

The energy is dissipated largely, or in some circumstances wholly, as heat developed

by viscous shear within the stream. A rather artificial but useful distinction can be made between (1) energy dissipated in friction along the wetted perimeter of the channel (external frictional losses), (2) energy dissipated in friction between the diverse threads of the turbulent current (internal frictional losses), and (3) energy consumed in the transportation of load. The external and internal frictional losses occur whether or not the stream is engaged in transportation; these losses increase with increase in roughness of the channel, with irregularity in the trend or alignment of the channel, and with any departure from the ideal semicircular cross-sectional form that provides the shortest length of wetted perimeter per unit of cross-sectional area. Roughness, alignment, and cross-sectional form are referred to as "channel characteristics"; they determine the "hydraulic efficiency" of the channel. On the basis of an analysis of Gilbert's experimental results and other data, Rubey estimates that the frictional energy losses account for 96% to 97.5% of the total energy in some debris-carrying streams, and that the remaining energy is utilized in transportation (Rubey, 1933, p. 503). The point emphasized here is that the share of the total energy that is utilized in transportation is very small.

Transportation of boulders and pebbles that move only if they are rolled or dragged along the stream bed, and of smaller grains that must be lifted again and again by turbulent currents consumes energy. These pebbles and grains move slower than the water—the energy required to put them in motion and keep them in motion varies with grain size and quantity. Transportation of ultra-fine or colloidal particles with negligible settling velocities (in still water) does not tax the energy of the stream.

If the energy in a given segment were not utilized within that segment an acceleration in the rate of flow would result. Since this is usually not the case it appears that the energy in most segments is equal to the energy dissipated within those segments (Gilbert, 1877, p. 106). This conclusion taken together with the fact that the energy dissipated in internal and external friction is overwhelmingly greater than that consumed in transportation means that, total energy determined by slope and discharge remaining the same, relatively slight changes in the channel characteristics cause very marked changes in transporting power. The practical engineer concerned, for example, with design of non-silting and non-eroding canals is well aware of this relationship (Lane, 1937). It is not given due emphasis in geologic textbook discussion of stream transportation.

The several factors that enter into this energy balance in streams may be recast in terms of velocity:

Velocity increases with increase in slope of the water surface.

Increase in discharge is accompanied by increase in (a) the cross-sectional area and (b) the wetted perimeter of the channel. Since the natural channel is approximately rectangular in section the cross-sectional area increases approximately as the product of width and depth, while the wetted perimeter increases approximately as the sum of the width and twice the depth. Cross-sectional area therefore increases relatively to wetted perimeter with increase in discharge, and this change results in a relative decrease in frictional retardation of flow. Primarily for this reason, velocity varies with discharge.

As the channel departs from the ideal cross-sectional form, or as the floor and walls vary from smooth to rough, or as the trend varies from straight to tortuous, there is an increase in external frictional retardation of flow due to increased length of the wetted perimeter relative to cross-sectional area, and also an increase in internal frictional retardation of flow due to increased turbulence. For these reasons, velocity varies with variation in the channel characteristics.

Velocity is, then, a measure of the energy content of the stream. It varies with any change in the total energy resulting from change in slope or discharge, and, total energy remaining the same, it varies with any change in the energy dissipated in external or internal friction, as defined earlier. To complete the picture of energy-velocity interrelations for the case of the debris-laden stream we have Gilbert's experimental data indicating that velocity varies inversely with the amount of energy consumed in the transportation of load (1914, p. 225–230).

COMPETENCE

Competence is defined by Gilbert as a measure of the ability of the stream to transport debris in terms of particle size; the familiar statement is that the weight of the largest particles moved by a stream varies as the sixth power of the velocity. It is well known that there are notable differences in velocity in different parts of the cross section of a stream; the term, as used in the expression above, is usually interpreted as the average velocity. Rubey states that competence actually varies as the sixth power of the "bed velocity", and that the bed-velocity formula gives "reasonably close estimates of the maximum size of particles transported by some large natural streams for which adequate data are available" (Rubey, 1938, p. 137). For purposes of the present discussion, the significance of Rubey's analysis and of the experimental data presented by Gilbert and numerous other workers in this field is simply that velocity required for transportation of detritus increases very markedly with increase in particle size.

The "sixth-power law" was formulated to express the velocity requirements of that fraction of the load of a stream which moves by sliding, rolling, and bouncing along the stream's bed, *i.e.* the tractional load or bed load. But a large part of the load of most natural streams is transported in suspension. The size of the largest particles that can be carried in suspension depends, not on velocity directly, but upon the intensity of turbulence within the stream (Leighly, 1934). Turbulence itself is, however, a function of velocity among other factors; intensity of turbulence increases with increase in velocity. Thus, while Rubey's sixth-power law does not apply to the transportation of suspended load, the decrease in velocity requirements with decrease in grain size probably continues through the range of the larger grain sizes that are normally carried in suspension. A considerable fraction of the suspended load may consist of ultra-fine or colloidal particles with negligible setting velocities; maintenance of these ultra-fine materials in suspension depends only negligibly upon velocity.

CAPACITY

"Capacity", as defined by Gilbert (1914, p. 35), refers to "the maximum load a stream can carry". The experimental data on which the competence principle was

based demonstrate also that, in a stream of given discharge, the velocity required for transportation varies with the quantity of any one grain size, the velocity requirements increasing with increase in the quantity or total weight of the material shed into the stream.

Gilbert used "capacity" in discussing data relating to transportation of weighed amounts of particles in the sand gravel size range under laboratory conditions. In spite of his explicit warning that his concept of capacity does not necessarily apply to natural streams (Gilbert, 1914, 223–230; *see also* Quirke, 1945) there has been a tendency so to apply it; the expressions "loaded to capacity", or "fully loaded", or "saturated with load" are frequently used in discussion of the graded condition in streams. These expressions are of course meaningless unless accompanied by some statement of the grain sizes or range in grade sizes which constitute the load. A stream "loaded to capacity" with coarse sand and pebbles could carry an enormously greater tonnage of material without change in velocity if the materials making up the load were crushed to silt size.

The capacity principle, like the competence principle, probably does not apply to the transportation of very small particles. Since the maintenance in suspension of ultra-fine clay particles and colloids (particles with negligible settling velocities) does not depend upon velocity, there is no theoretical upper limit to the amount of these materials that a stream of a given size and velocity can carry. A stream "loaded to capacity" with exceedingly fine particles would be a mud flow (Hjulström, 1935, p. 344–345).

There probably is in nature every gradation between normal streams and mud flows. Even the low concentrations of colloidal and ultra-fine particles that occur in normal streams undoubtedly tend slightly to increase carrying power by increasing the specific gravity of the water, and tend slightly to increase external and internal frictional energy losses by increasing the viscosity of the water. With higher and higher concentrations of these materials, particles of silt and sand and finally pebbles and boulders come to have negligible settling velocities in the medium until, in a mud flow, great blocks of rock can be carried buoyantly in a plastic mass that may move only a few feet an hour. These effects are negligible in normal streams.

THE TOTAL LOAD

Depending upon the lithologic characteristics, relief, and erosional processes in its drainage basin, and on processes in operation within the stream itself (as sorting), the range in grain sizes in the total load supplied to a given segment of a stream may vary widely. Moreover, the proportions of the several grain sizes in the total load may differ markedly in streams in which the range in grain size is the same. There is always, in normal streams, a decided "deficiency" in the supply of colloidal and ultra-fine materials.

Frequently the alluvial materials beneath and marginal to a stream channel include such an assortment of grain sizes that, as the velocity of the stream increases with seasonal increase in discharge, it is free to put in motion progressively coarser grain sizes up to the limits of its competence. There will be in this case a reasonably close relationship between the *quantity* of the debris in motion and the *largest grain*

sizes that are in motion at a given time. Partly on this basis, and using an expression for the "average settling velocity of all of the debris particles being transported", Rubey has developed a means for evaluating both competence and capacity relationships in terms of bed velocity: "in a stream free to pick up much sand and gravel as its velocity is increased, the unit width load will vary roughly as the third power of the 'bed' velocity" (Rubey, 1938, p. 139).

Rubey points out that this third-power principle applies only approximately in even those streams to which a fair proportion of the several movable grain sizes (excepting the ultra-fines) are available. In this case both competence and capacity might be said to be a function of velocity. But a stream completely adjusted to the transport of a large amount of sand and silt may carry no pebbles at all, due to a deficiency in supply, although gravel sizes are well within its competence. Gilbert's experimental proof that the quantity of load increases as the grain size decreases suggests that in this special case the total load per unit width of stream varies as a power of the bed velocity higher than the third power; it might be said that "capacity" is the critical factor in this case. A stream may, on the other hand, be supplied with a load consisting predominantly of pebbles and boulders, with a notably small proportion of sand. It appears that in this circumstance the total load per unit width of channel may vary as a power of the bed velocity lower than the third power; competence might be said to be the critical factor. (For an example of the significance of this point in a practical problem of design *see* Whipple's discussion of Missouri River slope, 1942, p. 1191–1200, 1212–1214.)

These numerical values, as such, are not important for purposes of the discussion to follow. But the possibility of notable variations in the proportions of the several grain sizes making up the total load, and the bearing of these variations (qualitatively) on the velocity requirements in the transporting stream, are important. Hereafter the expression "increase (or decrease) in load" means increase (or decrease) in the quantity and average grain size, in accordance with the case treated by Rubey. The expression "increase (or decrease) in calibre of load" means increase (or decrease) in particle size, the total load remaining the same.

THE CONCEPT OF GRADE

A graded stream is not then, strictly speaking, one in which there is "a balance between total energy and the work given the stream to do", or in which "energy supplied equals energy consumed"; a non-accelerating flow of water carrying no load in a flume or a bed-rock channel fulfills these requirements, but would hardly be considered graded in the geologic sense. It is not a stream in which "slope is adjusted to load"; the carrying power of a stream is a function of velocity, and slope is only one of the factors which bear on velocity. One of the attributes of a graded stream is a "balance between erosion and deposition", but definition of the condition of grade in terms of this balance, and emphasis on the "constant shifting" of the balance, is unfortunate because it focuses attention on incidental short-term changes in the activity of the stream and loses sight of the long-term balance which is the distinctive characteristic of the stream at grade. A graded stream is not a stream "loaded to

capacity" because streams never carry a capacity load (by Gilbert's definition). These definitions are partly or basically sound, but all of them include half-truths that are sources of confusion.

A graded stream is not in any sense a stream which is unable to abrade its bed because "all of its energy is used in transportation", or because "transporting the load requires all the energy that was formerly (during youth) applied to downcutting". The particles comprising the load are the tools used in abrasion, and since abrasion does not involve a dissipation of energy independent of that consumed in the propulsion of the tools, abrasion may be regarded as an incidental result of the bouncing, sliding and rolling motion of the particles.

A graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to absorb the effect of the change.

By *stream* we mean, of course, that particular segment with which we are directly concerned; many rivers have both graded and ungraded parts. The expression *over a period of years* rules out seasonal and other short-term fluctuations on the one hand and, on the other, the exceedingly slow changes that accompany the progress of the erosion cycle. *Load* and *discharge* deserve the prominence given in the definition not because they are the only or even necessarily the most important factors controlling slope, but because they are the only factors which are, *in origin*, wholly independent of the stream. *Slope* stands alone because it appears to be the only factor in the equilibrium which is automatically adjustable by the stream itself in such a direction as to accomodate changes in external controls that call for changes in velocity.

The balance involved in the condition of grade can be stated in an equation, but this method of expression is inadequate for present purposes because the terms of an equation are transposable. As set up in an equation, for example, load is a function of velocity. In answer to a query as to which is the cause and which is the effect, the average engineer will assert that velocity controls or determines the load that is carried by a stream; and he may have misgivings as to the sanity of the party who raised the question. In a flume or rock-floored torrent velocity does, in a sense, determine the load that can be carried. But, over a period of years, the load supplied to a stream is actually dependent, not on the velocity of the stream, but on the lithology, relief, vegetative cover, and erosional processes in operation in its drainage basin, and, in the graded stream, that particular slope is maintained which will provide just the velocity required to transport all of the supplied load. In this very real sense velocity is determined by, or adjusted to, the load. In the graded stream, load is a cause, and velocity is an effect: this relationship is not transposable.

The sections that follow approach the question raised by Kesseli as to the validity of the concept of grade by considering (1) typical examples of streams at grade, (2) factors that control the slope of the profile under stable conditions, and (3) reactions of graded streams to natural and artificial changes.

EXAMPLES OF STREAMS AT GRADE

A 50-mile segment of the Shoshone Valley east of Cody, Wyoming, contains a striking assemblage of river terraces, ranging from a few feet to several hundred feet above the stream. Inter-terrace scarps and the valleys of cross-cutting tributaries

FIGURE 1.—*River terraces near Cody, Wyoming*

Drawn by Allen S. Cary from photographs taken from Cedar Mountain looking eastward down the Shoshone Valley. The alluvial veneer shown on the front of the block includes Shoshone River channel gravel and overbank silts, and side stream fan deposits; these materials are wholly different in origin and appearance but cannot be distinguished on the scale of the drawing. Note truncation of bed rock structure along the terrace scarps. The rear scarp of the Powell Terrace is about 90 feet high, but is largely covered by alluvial fans and slope wash.

provide linear miles of exposures indicating that each terrace tread consists of a channeled and fluted rock floor, essentially flat in cross-valley profile, mantled by a uniformly thin (15 to 25 feet) sheet of alluvium. The rock floor of each terrace bevels inclined strata of varied types (Fig. 1). The mantle is made up largely of stream rounded pebbles wholly different lithologically from the local bedrock, and identical in composition with the detritus now being handled by the Shoshone River. The terrace surfaces and their planed rock floors exhibit smooth, concave-upward longitudinal profiles similar to that of the flood plain (Mackin, 1937, p. 825–837).

The manner of origin of the terraces is indicated by the present activity of the stream, which is meandering on its valley floor. Some curves are slicing laterally at the base of vertical to overhanging rock walls, and some are shifting downvalley from similar cut banks. As each meander shifts it leaves behind a grav-

elly surface exposed at low-water stage—it is safe to infer that the thickness of this channel gravel is at least equal to the depth of the channel. It is evident that the gravel deposit grows by lateral accretion as the stream shifts, and if, as seems likely, it rests on a rock floor, then this floor must have been cut by the shifting stream, *pari passu* with the deposition of the gravel. The gravel sheet represents the bed load; it is soon covered by fine silt and sand representing the finer fractions of the suspended load deposited by slow-moving or ponded overbank waters, and later by slope wash and side-stream alluvial fans. We do not *know* that the valley floor gravel sheet rests on bedrock because we canot see its base. But the gravel sheet on each terrace does rest on beveled bedrock, and edges laterally against the base of scarps with the same systematic curvature in plan as those being cut by the stream (Fig. 1).

These relations, taken together, indicate that the terraces are remnants of valley floors cut in bedrock by the lateral planation of the Shoshone River during earlier periods of very slow downcutting or pauses in downcutting (Mackin, 1937). They are altogether different in origin and structure from the equally valid type of terrace formed by partial filling of a valley and later trenching of the fill. And they most certainly were not formed by incidental deposition of gravel (as by floods?) on surfaces produced by other erosional process (successive downstepping peneplanes?); in that they were formed by the same agency at the same time, the gravel veneers are related directly, not incidentally, to the planed surfaces on which they rest.

Individual terrace remnants in the Shoshone Valley are more than half a mile wide and a higher Shoshone valley floor (Pole Cat Bench) is over 2 miles wide and essentially flat in cross profile. In the opening out of valley floors of such great breadth the river must have shifted repeatedly from side to side, trimming back first one valley side and then the other. As indicated above, the stream is now engaged in the same activity on a valley floor with an average declivity of more than 30 feet per mile; the slope of the earlier valley floors is (and was) of the same order of magnitude. Since streams of similar discharge and channel characteristics are now vigorously cutting downward in rock with much lower slopes, the question arises as to what held in check the downcutting of the high-gradient Shoshone during the very long period of planation. Bedrock resistance can be readily ruled out as a controlling factor, for the valley is underlain by sandstones and shales, and such contrasts in resistance as do occur are not reflected in the profiles of the present stream or the terraces. Even more compelling is the fact that the river has repeatedly opened out very broad valley floors by lateral corrasion in the same bedrock during periods when its downcutting was negligible.

The Shoshone failed to trench its valley floor during the terrace-cutting stages, and the present stream fails to trench its present valley floor because its high gradient is perfectly adjusted to provide, with available discharge and with the prevailing channel characteristics, just the velocity required for transportation of a large load of coarse rock waste continuously supplied to it from ramifying headwaters in the rugged Absaroka Range. Adjacent ephemeral streams that head on the arid floor of the Bighorn Basin and are supplied only with fine-textured detritus maintain lower slopes than the master streams that head in the mountains, although their discharge

is only a small fraction of that of the master streams (Mackin, 1936; see also Rich, 1935, and Hunt, 1946, for parallel cases in Utah). Water diverted from the Shoshone River and freed of bed load must be conducted down the terrace surfaces in concrete canals or in canals interrupted by concrete dams; it would otherwise entrench itself below the headgates of the laterals. The "velocity required for transportation" is such that the river rolls and bounces 8 to 12 inch boulders along its bed. The river bed is so efficient a grinding mill that boulders of such rock types as dense andesite are reduced in diameter by one-half within a few tens of miles. But the velocity requirements for transportation are so definitely fixed that the river, flowing over sandstone and shale, could not lower its slope by downcutting during the planation stages, and is not able to cut down at the present time. If the slope were altered, as by warping, the river would be forced to restore it by cutting or filling as the case might be. The Shoshone east of Cody was during the planation stages, and probably is at the present time, a typical graded stream.

Valleys of tributaries of the Columbia River system, particularly those of the Clark Fork and Spokane rivers, illustrate the same additional relationships even more strikingly than the Shoshone Valley. These Columbia Basin valleys were partly filled with glacial, glacio-fluvial, and glacio-lacustrine deposits during the Pleistocene and have since been partly re-excavated. Here again, we look to terrace remnants of higher valley floors because exposures in the dissected terraces supply morphological data that could be obtained from the present valley floor only by hundreds of borings. The postglacial stream terraces (not to be confused with a wide variety of other types of terraces produced during the period of ice occupancy) usually consist of a sheet of channel gravel, 10 to 30 feet thick, overlain by typical overbank silt plus loess and slopewash from higher valley sides. The gravel sheet rests on a channeled and fluted surface which truncates disordered structures in till, lake clays and silts, older gravels, and bedrock; deposition of the gravels accompanied the cutting of the surface on which they lie. The longitudinal slopes of the terraces and of the present valley floors range from 5 feet per mile upward and the larger common pebble sizes in the terrace gravels and the present river bars approximate 6 inches in diameter. It is useful to consider how rapidly, in so far as scouring power is concerned, large streams carrying coarse gravel on these high slopes could trench downward in silt, and at the same time to note that the streams opened out broad valley floors by lateral planation in silt and bed rock in adjoining segments of their valleys, without trenching. The high longitudinal slopes were maintained during the planation stages simply because these slopes were required to provide the velocity needed for transportation of detritus continuously supplied to the streams; for emphasis through hyperbole, one might say that they would have been so maintained had the subjacent materials been cream cheese.

These high-gradient streams were selected as examples to indicate at the outset that the term grade carries no connotation of low declivity. The low-gradient Illinois River is, as Rubey states, an excellent example of a stream in equilibrium (1931) but it is no more excellent than the Columbia tributaries, the Shoshone, the Mesa-stage Rock Creek (Montana) with a slope of about 90 feet per mile (Mackin, 1937, p. 848–850), or many Southwestern pediment streams with much higher slopes (Bryan,

1922). The classic examples are, of course, the wet-weather streams that carved Gilbert's planation surfaces around the flanks of the Henry Mountains in Utah (1877). If, as suggested by some engineering articles, the adjusted stream is one that is stable in channel form and position (Pickels, 1941, p. 166) then the (engineering) adjusted stream is only one special type of the (geologic) graded stream, which is stable only in slope.

The Columbia tributaries are useful also as examples because these streams are at many points locally superposed from the fill onto rock knobs and spurs, some of which have caused falls or rapids now and during earlier planation stages. These streams consist, in other words, of graded segments separated by segments that are not graded, but this circumstance is certainly no defect in the theory of grade.

THE GRADED STREAM AS A SYSTEM IN EQUILIBRIUM

The idea that a balanced or adjusted condition in streams is an expression of an equilibrium relationship, and that the graded profile is a slope of equilibrium is one of the oldest and most useful of geological concepts relating to streams. Many geologists seem to try to make their treatment of the balanced condition conform to the rigid definition of equilibrium used in the sciences of physics and chemistry. This point of view is reflected in the stock statement that the equilibrium is constantly shifting, approached, but rarely or never attained in the seasonally varying stream. It reaches its logical climax in Kesseli's argument that since discharge, velocity, and other factors are not literally constant in natural streams, no equilibrium can exist.

The requisite conditions for chemical equilibria (as between water and water vapor in a closed container) are; (1) absolute constancy of external controlling conditions (as temperature), and (2) a literally perfect balance between opposed tendencies (as the hail of molecules leaving and returning to the surface of the water). If the water-water vapor apparatus is housed in a laboratory where it is affected by constantly varying diurnal temperature changes, then, strictly speaking, the system rarely or never attains the perfect equivalence between opposed processes which is the essential mark of chemical equilibria. There is, moreover, in the precise chemical sense, a shifting between different states of equilibrium, but there is no such thing as a shifting equilibrium.

(1) *Constancy of controlling conditions* is certainly absent in any segment of a graded stream if attention is focused on its activity during any short period of time, as a year or part of a year. All natural streams vary in discharge, and in many the ratio of high-water to low-water discharge is several hundred to one. In some fully graded stream-transportation systems (in the geologic sense) there may be no discharge at all for most of the year. Velocity, load and all the other factors which enter into the economy of the balanced stream vary markedly with variations in discharge.

(2) *The perfect balance between opposed tendencies*, as an interchange between particles at rest on the bed and in motion in the stream, is not maintained in natural streams. In general, a stream flowing over alluvial materials within its competence tends to enlarge the channel during high-water stages, not only by increase in the height of the water surface, but also by scouring the bed. With decrease in discharge

and slackening in velocity as the high-water stage recedes, the stream deposits that part of the load which it is no longer able to carry. Indeed, the same change in controlling conditions may give rise to opposite changes in different parts of the same channel at the same time; increase in discharge and velocity usually causes, for instance, scouring on bends and filling on "crossings" in meandering streams (Straub, 1942, p. 619).

Kesseli, implying (1941, p. 580) that Davis was not aware of seasonal variations in discharge and velocity in natural streams, misses the point. Davis considered the stream as an agent of transportation over a period of years—he was concerned with the forest rather than the trees. Over a period of years sufficiently long to include all the vagaries of the stream, the two independent controls (discharge and supplied load) may be essentially constant. Whatever the conclusions from *a priori* reasoning as to whether constancy of these conditions *should be* maintained in nature, *a posteriori* reasoning based upon the existence of widespread corrasion surfaces of the type represented by the Shoshone terraces indicates that they *are* so maintained long enough to produce distinctive land forms.

Scouring and filling with seasonal fluctuations in discharge and velocity occur in all streams; it is the peculiar and distinctive characteristic of the graded stream that after hundreds or thousands of such short-period fluctuations, entailing an enormous total footage of scouring and filling, the stream shows no change in altitude or declivity. Here again the extensive stream-planed rock surfaces of the Shoshone Valley, with their thin veneers of alluvium, are a case in point. In this long-term sense, there is an equivalence of opposed tendencies in the graded stream.

The concept of equilibrium is the basis for modern quantitative treatments of stream transportation; Rubey's mathematical analysis of "capacity" is appropriately entitled *Equilibrium conditions in debris-laden streams* (1933). The origin and significance of slope variations in the longitudinal profile of the graded stream under stable conditions can be understood only in terms of equilibrium relations. In its sensitivity to change, and its tendency to readjust itself to the changed conditions, the graded stream exhibits the chief and diagnostic mark of a system in equilibrium. It is, in other words, useful and necessary to consider a graded stream as a system in equilibrium, and it is altogether proper so to consider it, provided that it is stated explicitly that the type of equilibrium is different in mechanism and detail from the types treated by the chemist and the physicist, and from the equally valid types recognized by the zoologist and the botanist.[1]

Recognition of these differences eliminates the need for apologetic statements, seemingly made in deference to the chemical usage, to the effect that the stream shifts with every short-period fluctuation from one state of equilibrium to another, or toward another which it never quite attains. To the extent that this view has been the vogue, Kesseli's statement that the condition of grade is "elusive" is amply justified. Distribution of discharge over a short period of time, whether essentially uniform or largely concentrated in rare floods, has much significance with regard to the charac-

[1] For discussion of equilibrium as a "universal law" of wide application *see* W. D. Bancroft's Presidential Address to the American Chemical Society (1911). *See also* "The principle of dynamic equilibrium" as applied in Oceanography (Sverdrup *et al.*, 1942, p. 160).

teristics of the stream, and it is true that the greater part of the work of all streams both in erosion and transportation is accomplished during high-water stages. But whether the slope of the profile is determined during a brief annual period of high water (Baulig, 1926, p. 59) during the longer period of low water, or during some "bedforming stage" (Schaffernak, cited by Schoklitsch, 1937, p. 144) need not concern us here. It is not the particular stage of the stream in flood or low water, but the stream operating "over a period of years" that is the natural unit; the balance automatically maintained in this unit is, in its own way, quite as perfect as that of the most delicate equilibria dealt with in the "precise sciences".[2]

THE SHIFTING EQUILIBRIUM

The expression "over a period of years" was used advisedly in the statement above regarding the essential constancy of controlling conditions; all of the conditions are subject to change over a period of geologic time. The changes may be sudden, or they may occur at a rate corresponding with the slow progress of the erosion cycle. Other things being equal, the manner in which the stream responds to changes is determined by the rate at which they occur.

A once-graded stream may, in response to a change tending to cause downcutting, (1) lower itself so slowly that each of its slightly lower profiles is maintained in *approximate* adjustment to that phase of the slowly changing conditions in existence at the time of its formation or, (2) be transformed by a relatively sudden change into a wholly unadjusted series of waterfalls and rapids, and re-establish a graded profile at a lower level only after a considerable lapse of time.

Similarly, a graded stream may (3) respond to slow uplift of a barrier across its path by upbuilding, each of its successively higher profiles being in *approximate* adjustment to the conditions at the time of its formation. Rate of uplift of the barrier may, on the other hand, (4) so far outstrip the rate of filling that a lake basin is formed. The stream will in this case develop a new graded profile only after a period of delta building following cessation of uplift.

In cases (2) and (4) the streams were clearly ungraded or out of equilibrium during the transitional periods. The sharply contrasted condition of the streams in cases (1) and (3) may be thought of as representing a *shifting equilibrium*. Use of this expression to indicate maintenance of approximate adjustment to a long-term change in control is justified by the fact that it describes what actually occurs.

In the discussion to follow it will be necessary to return again and again to the contrast between processes in operation in the stream in which the condition of equilibrium is maintained, the stream in which the equilibrium is shifting, and the stream in which there is no semblance of equilibrium. The landforms and deposits

[2] It is useful in this connection to look again at the water-water vapor system, this time focusing attention on the smallest conceivable surface area of water. It will be noted that *two* molecules may leave the water surface and only one return to it in any exceedingly short period of time. The level of the water surface is lowered. In the next unit of time two molecules return and only one leaves; the surface of the water returns to its former position. The point is that time and space relationships must enter into any consideration of equilibria. The time and space relations of the balance in graded streams are of a wholly different order of magnitude from those that obtain in the chemist's laboratory, but the perfection of equivalence of opposed tendencies is none the less perfect.

associated with these three conditions show differences that are of special significance to the geologist, but his terminology includes no simple and definitive terms for distinguishing them. It is therefore suggested, in accordance with Davis' (1902, p. 107) original proposal that "graded" be used specifically for the stream in which equilibrium is maintained, and that "degrading" and "aggrading" be restricted to cases of the shifting equilibrium. "Degrading" is downcutting approximately at grade, in contradistinction to such self-explanatory terms as trench or incise. "Aggrading" is upbuilding approximately at grade. "Regrading" refers to alteration in the form of the longitudinal profile by simultaneous aggrading and degrading in different parts (Johnson, 1932, p. 662). The term "degrade" is still available, of course, to describe the modeling of waste slopes in interstream areas.

There is no justification or need for using either "aggrade" or "degrade" to describe short-period variations in stream activity, that is, as synonyms for "filling" or "scouring" (of a channel), or for the more general terms "erosion" and "deposition". The following quotations from the last edition of an outstanding and most influential textbook illustrate, from the point of view of the present paper, a misuse of terms. The numbers in brackets are inserted for convenience in reference.

"(1) As downcutting reduces the gradient . . . a time comes when the increasing burden of transporting the load requires all of the energy that was formerly applied to downcutting. . . . The long profile has become a *profile of equilibrium* and the stream is said to be *graded*. (2) When a part of a main stream reaches grade, the local tributaries soon become graded with respect to it. (3) Any change in gradient, discharge, or load would upset the graded condition by altering the rate of erosion. A flood, for example, might convert the graded stream into one actively degrading, but with subsidence of the flood the graded condition would be restored. (4) Again, great increases in load are known to have converted graded streams into actively aggrading ones; for example, when glaciers appearing in their headwater regions poured great additional quantities of rock waste into them". (Longwell, Knopf and Flint, 1939, p. 64–65).

The view expressed in (1) has been discussed earlier; downcutting, or abrasion in general, does not involve an expenditure of energy independent of that consumed in friction and transportation of load. In (2) the term grade is used in what the present writer regards the proper long-term sense, but in (3) it is used in a wholly different short-term sense. In (3) the term degrading is synonymous with deepening of the bed by scouring (this usage involves a situtation in which the *surface of the water is raised* when the stream is said to be degrading!). If a stream responds to a flood by degrading it presumably restores the graded condition by aggrading when the flood subsides. But in (4) aggrading is used to describe the response of a stream to a completely different long-term change in controlling conditions.

While no importance attaches to the terms, as such, it is the writer's opinion that the usage illustrated by these quotations is at least partly responsible for the confusion that forms the basis for Kesseli's attack on the theory of the graded river. The usage suggested here emphasizes the contrast between seasonal fluctuations in stream activity (or, indeed, the equally striking diurnal changes in certain proglacial streams) and such true shiftings of the equilibrium as those represented by epicycles of valley cutting and filling in the Southwest (Bryan, 1940; Bailey, 1935). The distinction is analagous to that made by the meteorologist between weather and climate, and it is just as fundamental. In addition, the proposed usage differentiates between the equilibrium that shifts in response to long-term change and the equilibrium that is

maintained long enough to permit the stream to produce the distinctive landforms mentioned earlier. A question may arise as to the exact line of demarkation, in terms of feet of degradation or aggradation during so many thousands or millions of years, between the graded stream and the stream that is degrading or aggrading very slowly. Argument on this score leads nowhere—we classify natural phenomena not to assign each member of a series to a numerical pidgeonhole, but to clarify our understanding of their interrelationships. The distinction between the graded and the slowly degrading stream must, and should properly, depend on the nature of the problem and the point of view of the investigator.

FACTORS CONTROLLING THE SLOPE OF THE GRADED PROFILE

GENERAL STATEMENT

Longitudinal profiles of graded streams are often considered to be smooth, "concave upward" curves, that is, curves that decrease systematically in slope in a downvalley direction. Systematic downvalley decrease in slope is, however, by no means an essential or necessary attribute of the graded profile. The stream receives contributions of water and debris from every part of its drainage basin, but the additions are concentrated largely at tributary junctions and the ratio of water to debris varies markedly from place to place, from the high-water ratio of a tributary issuing from a lake or other natural settling basin to the high-debris ratio represented by a talus slide. Superposed on, and in part the result of, the changes in load and discharge are changes in the channel characteristics; these affect the hydraulic efficiency of the channel and hence the slope of the stream.

Such changes along its length might seem to count against considering the graded stream a system in equilibrium, or to indicate that it should be regarded as a type of shifting equilibrium. Indeed, comparison of the manner in which a stream accomodates itself to changes in control from segment to segment under stable conditions with its reaction to a change in conditions (as warping or a climatic change) is a useful mental exercise. But these two types of changes are completely different in origin, and it would be fatal to confuse them in analysis of a given longitudinal profile. While the velocity of each unit segment of a graded stream under stable conditions differs from that of adjoining segments (being kept in balance with local variations in velocity requirements by appropriate adjustments in slope) the close interdependence between all of the segments is such that they are parts of one well-defined system. Factors bearing on the slope of the longitudinal profile that is *maintained* without change as long as conditions remain the same are considered in this section.

DOWNVALLEY INCREASE IN DISCHARGE

It is a matter of observation that large graded streams usually have lower slopes than smaller graded streams. Similarly, a graded stream formed by the confluence of two graded streams usually has, below the junction, a slope lower than that of either of the confluents. The essential reason for these relations, mentioned earlier, is that with increase in size of the channel there is usually an increase in cross-sectional area relative to wetted perimeter and a consequent relative decrease in frictional

retardation of flow. A result is that large streams commonly have higher velocities than smaller streams with the same slope, or, stated in terms of the profile of a single stream, a downvalley segment with large discharge can maintain a given velocity on a lower slope than an upvalley segment with small discharge. In other words, a mere downvalley increase in discharge requires (or permits) a corresponding downvalley decrease in the slope of the graded profile.

DOWNVALLEY INCREASE IN RATIO OF LOAD TO DISCHARGE

Trunk streams often head in regions of high relief and flow in their lower portions through regions of relatively low relief. Under these circumstances the ratio of total load to discharge in the contributions of tributaries may be larger in the lower than in the upper parts of the stream. For the same reason, the caliber of the load supplied to the stream by tributaries, slope-washing, creep, and talus fall commonly decreases from head to mouth. Downvalley decrease in total load relative to discharge and/or downvalley decrease in the caliber of load shed into the stream, to the extent that they occur, require a corresponding downvalley decrease in the slope of the graded profile.

DOWNVALLEY DECREASE IN RATIO OF LOAD TO DISCHARGE

The load of a graded stream may increase in a downvalley direction relative to its discharge because of evaporation or subsurface loss of water, or as a result of the entry of heavily loaded tributaries and various slower types of mass movement from its valley sides. Kesseli particularly emphasizes the latter process as being incompatible with the concept of grade, his statement being that if a stream be "fully loaded" it is manifestly impossible for it to acquire additional load as, for instance, the material caving from banks undercut in the process of valley floor widening (1941, p. 578). This statement is roughly equivalent to the contention that a given saturated solution, in the presence of excess of the solute, cannot take more of that substance into solution. The solution can and must, of course, become more concentrated if any change in control, as an increase in temperature, displaces the equilibrium in the proper direction. Similarly, the graded stream can accommodate itself to the transportation of increased load at any point; it usually does so by a local increase in declivity.

Steepening of the Missouri profile at and below the junction of the Platte River is a case in point. The average declivity of the Missouri for 31 miles above the mouth of the Platte was .74 feet per mile as measured in 1931, and the average slope for 44 miles below the junction was 1.24 feet per mile (Whipple, 1942, p. 1185—in the original report by Straub, cited by Whipple, slopes for unspecified distances above and below the junction are given as .68 and 1.16 feet per mile, respectively; Straub, 1935, p. 1145). The slope of the lower part of the Platte is 3.2 feet per mile. Steepening of the Missouri profile is ascribed by Straub and Whipple to entry of the heavy gravel bed load of the Platte into the Missouri, which carries chiefly sand and silt above the junction. On the basis of an extended study of Missouri slopes and load, Straub generalizes as follows: "As is to be expected, the steepest part of the Missouri River below the point of confluence of the Yellowstone is in the vicinity of the mouths of the tributaries adding the largest bed load" (Straub, 1935, p. 1145).

It should be emphasized that entry of the Platte gravels into the Missouri is not due to any recent change in conditions. The local steepening of the Missouri profile is *not* a matter of "deposition" of gravels by the Platte at its mouth because the Missouri is unable to carry the load. If this were so the streams would be upbuilding rapidly, which is not the case. The Missouri profile below the junction is just steep enough to permit the stream to carry *all* of the added load. The profile break has been and will be maintained without change as long as conditions remain the same, which is the same as saying that the Missouri is graded above and below the junction.

Additions to the load of a graded stream resulting from various types of mass movements of the type mentioned by Kesseli are accomodated in the same way. The fact that nearly all streams receive detritus from these sources and, nevertheless, usually maintain smooth concave-upward profiles past the individual caving banks means simply that these additions are usually so small, relative to the great bulk of rock waste in process of transport along the channel in any given period of time, that their effects on the longitudinal profile are usually lost to view in the general downvalley lowering of declivity resulting from the other changes discussed in this section.

Increased slope of the Missouri at and below the Platte junction is required to provide increased velocity needed for transportation of the increased bed load, but this is not the whole story. The Missouri, a meandering river above the Platte junction, is characterized at and below the junction by a broad irregular channel with numerous bars. This change in habits, a result of the added bed load, almost certainly increases frictional retardation and, hence, calls for a steepening in slope to permit development of any given velocity by the Missouri. In other words, the effect of the Platte is two-fold—the total steepening of the main stream profile represents the adjustment required to accomodate both the direct and the indirect effects of the influx of Platte gravels.

DOWNVALLEY DECREASE IN CALIBER OF LOAD

Graded profiles usually decrease in slope in a downvalley direction between tributary junctions, chiefly because of a downvalley decrease in caliber of load due to processes within the stream. The principle involved is that the velocity (and, other things being equal, the declivity) required for the transportation of the coarser fractions of a stream's load decreases with decrease in grain size, the total amount of the load remaining the same. The operation of this principle in natural streams is best illustrated by consideration of a graded segment without tributaries, in which additions and loss of water and detritus are negligible.

The lower portion of the Greybull River in the Bighorn Basin, Wyoming, approximates these ideal conditions. The river issues from the Absaroka Mountains and flows through the arid lowlands of the Basin to its junction with the Bighorn River, receiving its last perennial tributary (Wood River) about 50 miles above its mouth. A peculiar drainage pattern that delivers most of the intermittent drainage from immediately adjacent lowland areas to the Bighorn River by independent streams and an analysis of available discharge records provide reasonable assurance that there is no significant increase in the discharge of the Greybull in the 50-mile segment below Wood River. Throughout this segment the stream is meandering on a valley floor wider than the meander belt. Since the stream is neither aggrading nor degrading at a rate that would be appreciable over a period of years,

the total load passing through all parts of the 50-mile segment in a given interval of time must be essentially the same, or may increase slightly downvalley as a result of bank erosion and other processes. In other words, variations in ratio of discharge to total load are of minor importance.

The profile of the Greybull valley floor decreases in slope from about 60 feet per mile at the head of the 50-mile segment to about 20 feet per mile at the lower end; that is, the profile is strongly "concave upward". Stream-cut rock terraces ranging from 50 to 1200 feet above the present stream show a similar eastward (downvalley) decrease in slope. The river was certainly in essentially perfect adjustment during the long periods of lateral planation recorded by the terraces and probably still is. The downvalley decrease in slope must in this case be ascribed largely to a decrease in caliber of load in transit; pebbles of the valley floor and terrace gravel sheets decrease notably in size in a downvalley direction (Mackin, 1937, p. 858–862).

Discussions of the form of the graded profile often neglect downvalley decrease in caliber of load as a control, or, what is worse, imply that this decrease is the *result* of the decrease in slope. Discussion of this point belongs in a later section; it is sufficient to state here that downvalley decrease in caliber of load is an important cause of downvalley decrease in the slope of the graded profile, and that, in the graded stream, the decrease in caliber is due primarily to attritional comminution of particles comprising the load.

The bearing of decrease in caliber of load due to attrition on the slope of the graded profile is particularly emphasized in the European literature. Schoklitsch, for example, cites Sternberg to the effect that certain central European rivers show a systematic decrease in the weight of particles comprising the bed load as a function of distance traveled. He then points out (1) that "An examination of the profiles of natural watercourses reveals the striking fact that, with few exceptions, the slope (like the size of the bed-sediment particles) decreases from source to mouth"; (2) that it is therefore "quite logical to attempt to ascertain a relation between this law [the Sternberg law of decrease in particle weight] and the shape of the profile, at least in the stretches in which the reduction in size of the particles is due to abrasion"; and finally, (3) that "study of a number of river profiles showed that the slope ... is proportional to the particle size". On this basis Schoklitsch develops an equation for the river profile (1937, p. 153). Many other writers have advanced the theory that graded or adjusted river profiles are mathematical curves, often without Schoklitsch's qualifications as to the effect of tributaries. The most recent contribution in this country (Shulits, 1941) presents a so-called "Rational equation of river-bed profile". The theory that longitudinal profiles closely approximate simple logarithmic curves has been utilized in geomorphic studies, chiefly in England. (*See*, for example, Jones, 1924; and Green, 1936; for critical discussion see Miller, 1939; and Lewis, 1945.)

Analysis of the mathematics of the graded profile and its important geomorphic implications lies beyond the scope of this article. The following will indicate how the theory applies in this qualitative treatment of the concept of grade:

Rubey, discussing the Shulits article, points out (1) that the Shulits equation is empirical rather than "rational"; (2) that many factors other than caliber of load bear on the slope of the profile, and (3) that the profile of a stream could vary directly as a power of bed-load diameters only if there were some "complex and as yet unformulated interrelationships among the many other variables" (p. 630).

The fact is, of course, that there can be no such interrelationships because there is

no interdependence of all the factors bearing on slope in a trunk stream. The contribution of each tributary to a main stream is conditioned by the rocks, relief, and climate in the tributary drainage basin and is not systematically related to relationships in the main stream above the point where the tributary happens to enter. Changes in slope such as that caused by the Platte occur elsewhere on the Missouri, as indicated by Straub's generalization; in high-gradient western streams with which the writer is familiar these changes are even more striking than on the Missouri. The effect of tributaries is only one of several types of change along the length of the stream which are neither interdependent nor systematic. Mathematics can be an exceedingly useful tool in the study of river profiles, but it seems to the writer that the attitude that considers the job to be done because an *approximate* overall fit is obtained in the matching of curves is basically wrong; slurring over the irregularities gives a false impression of simplicity. Some types of numerical values, as the percentages of the several grain sizes in samples of sand and gravel, yield significant averages. But precise altitudes of points along a river profile are not subject to sampling errors; insofar as any understanding of its origin is concerned, the *breaks* in a semi-log plat of the profile are the significant elements, and a single straight line drawn through scattered points has little meaning. Downvalley decrease in caliber of load by reason of attrition is more nearly systematic than any of the other factors bearing on the slope of the graded profile. But caliber of load does not vary systematically in graded streams joined by tributaries, nor in graded streams in which the rock types in the load differ notably in resistance to attrition; even if it did, caliber of load is only one of a number of partly or wholly independent factors controlling the graded slope.[3]

RELATIONSHIP BETWEEN CHANNEL CHARACTERISTICS AND SLOPE

As indicated earlier, the hydraulic efficiency of a channel varies with the channel characteristics; self-evident theoretical considerations and experimental data establish this point so clearly that it needs no discussion here. Close relationship between efficiency, as determined by channel characteristics, and slope of the graded stream is demonstrated compellingly by the reduction in slope from about .96 to about .69 feet per mile in a few years, as a result of artificial smoothing of tortuous curves and narrowing, and consequent automatic deepening, of parts of the Missouri channel (Whipple, 1942, p. 1199). The overall length of the channel was not significantly changed by the channel improvement measures. In terms of velocity the essential reason for the reduction in slope is that a reduction in frictional retardation of the current in the corrected channel permits the stream to develop the velocity required for transportation of its load on a lowered slope. In terms of energy the

[3] Slopes of ungraded stream segments are determined by the depth to which the stream has cut downward. In headwater basins in bed rock fairly uniform in resistance to corrasion the ungraded profile tends to decrease in declivity in a downvalley direction, the reason being downvalley increase in discharge and therefore corrasive power. Ungraded profiles of this type are superficially similar to graded profiles but they are completely different in origin; the ungraded profile is conditioned by the corrasive power of the stream, bed rock resistance to corrasion, and the length of time that the stream has been downcutting, while the graded profile is an adjusted slope of transportation that is influenced negligibly, if at all, by these factors. Mathematical analysis of a stream profile that fails to distinguish between graded and ungraded segments involves the fundamental error of mixing different types of data, and can lead only to frustration or to conclusions that are unsound.

explanation is that a reduction in "internal" and "external" energy losses in the improved channel causes an automatic adjustment of slope of such nature as to reduce the total energy of the stream, the energy utilized in transportation remaining the same.

Because different segments of graded streams vary widely in channel characteristics, these variations certainly bear on the overall form of the longitudinal profile. But before discussing these effects it is necessary to consider a fundamental question regarding the theory of grade.

THE CONCEPT OF ADJUSTMENT IN SECTION

The channel characteristics of a graded stream, like its slope, are developed by the stream itself. Both slope *and* channel characteristics vary from segment to segment, and any change in external controls usually results in changes in both of these variables. Because of the nature of his work the attention of the geologist is usually focused on slope; he knows, for example, that a graded stream responds to changes in load due to waxing and waning of glaciers in its drainage basin by appropriate adjustments in slope effected by upbuilding or downcutting. The attention of the engineer is, on the other hand, usually focused on the channel characteristics; he can, for example, enable an "adjusted" stream to transport an influx of mine waste that greatly increases its load by appropriate channel-improvement measures, without change in slope. A question arises, then, as to whether the foregoing definition which describes the graded stream as one "in which *slope* is delicately adjusted", etc., should not be revised to read, "in which *slope and channel characteristics* are delicately adjusted," etc.

That the question is a very real one is indicated by recent discussion of transportation by running water in the engineering literature which emphasizes especially the concept of the "adjusted", or "stable", or "regimen" (in the sense of equilibrium) cross-sectional form.[4] The discussion centers around problems of design of nonsilting and noneroding canals of various types. (Lane, 1937, with bibliography and discussion by 10 writers; important British papers include Griffith, 1927; and Lacey, 1930); but theoretical aspects of the relationship between cross-sectional form and transportation necessarily apply to natural streams. For example, Griffith observes (A) that natural streams with heavy bed load tend to flow in broad, shallow channels. He concludes (B) that the broad, shallow channel is the type of cross section best adapted for the transportation of heavy bed load. The general attitude of mind that makes (B) follow from (A) is expressed as follows: "A river fully charged with silt [meaning, in the geologic usage, debris without regard for particle size] *must obviously tend to adopt that form of section which will give it a maximum silt-carrying capacity*" (Griffith, 1927, p. 251) (italics mine).

[4] I am indebted to W. W. Rubey for calling my attention to the need for somewhat more extended discussion of the concept of adjusted cross sections than was accorded that concept in an early draft of this article examined by him. He kindly loaned me an unpublished manuscript on the Hardin-Brussels quadrangles in Illinois, in which the channel characteristics of the Illinois River are analyzed mathematically (for published abstract, *see* Rubey, 1931a), and subsequent correspondence with him clarified and extended my own views. These views do not parallel his in all respects, and he is not responsible for them. But I would like to emphasize that everything that may have lasting value in this section is an outgrowth of his council.

There is perhaps deductive ground for believing that all the characteristics of natural channels, if they are to be "permanent", must somehow contribute to the ability of the stream to transport debris. It might be argued in the same deductive vein that the principle of "least work" would lead one to expect that changes in channel characteristics caused by a change in controlling conditions must be "adjustments" in that they must be of such nature as to adapt the stream to the new conditions. Analysis of the extent to which channel characteristics *are* adjustable in this sense may begin by considering channel-modeling processes in a straight channel in which movement of coarse-textured debris depends on velocity.

ADJUSTMENT IN SECTION IN THE STRAIGHT CHANNEL

The semicircular section that would provide the least frictional retardation of flow for clear water or for water carrying only ultra-fine or colloidal particles is rarely or never developed or maintained by flowing water charged with coarse debris for many reasons, the more important of which are: (1) a large bed load requires high bed velocity and widening by bank erosion that must continue until velocity at the banks is reduced to the point where the resistance to erosion of the bank-forming materials equals the erosive force applied to them. (2) Shoaling by deposition will accompany widening of the narrow channel by erosion because the particles of the bed load tend to lodge, and move, and lodge again, the velocity required each time to set them in motion being greater than that required to keep them in motion, and because a higher velocity is required to set in motion a particle on the bed than one on the sloping banks. The operation of these processes results in a channel that is, under different circumstances, semielliptical (Lacey, 1930, p. 273; Lacey in discussion of Lane, 1937, p. 160) or parabolic (Pettis, in discussion of Lane, 1937, p. 149–151) in section, and this section, once developed by automatic modification of an originally too narrow or too wide section, will be stable, or in adjustment, or regimen as long as conditions remain the same. But it does not follow that the channel so formed will necessarily provide the "maximum silt-carrying capacity."

Widening causes (1) reduction in bed load moved per unit width of bed by reason of decrease in velocity that accompanies decrease in depth, and, at the same time, (2) increases the length of the cross section (that is, the number of width units) through which the bed load is moved. Tendencies (1) and (2) are opposed insofar as transportation of bed load is concerned; especially because of (2) the cross-sectional form that provides maximum efficiency for transportation of debris is wider and shallower than the semicircular section that gives maximum efficiency for movement of water. The form of the cross section most efficient for transportation varies with slope, with amount and caliber of the load, and especially with the proportions of the total load that are carried in suspension and moved along the bed. These factors are partly interdependent, and they certainly influence the form of cross section that is developed and maintained by the stream. But the form of the cross section depends also, for reasons indicated above, on a factor wholly independent of the stream, namely, resistance of the banks to erosion. For any one set of slope-debris charge factors there will be one critical degree of erodibility of the bank-forming materials such that an originally too narrow channel will quickly develop a cross section with

depth-width relations that provide "the maximum silt-carrying capacity". If the bank-forming materials are less erodible than this critical degree the stream may tend to develop the maximum efficiency section over a period of time; that is, the final stable channel section, however long delayed, may approximate the ideal form for the given slope-debris-charge factors. But if the bank-forming materials are more erodible than the critical degree the stream will adopt and maintain a section that is wider and shallower than the ideal transportation section. In the case of the high-slope stream carrying coarse gravel between banks of incoherent sand, widening may continue until the channel disintegrates into a plexus of split channels and gravel bars that is the antithesis of efficiency for transportation. In this case, and generally, the operation of the "least work" principle is merely a matter of expediency and compromise with local conditions—the river braids because an arrangement of minor channels and bars is somewhat less inefficient than a single exceedingly wide and uniformly shallow channel.

It appears, therefore, that a statement to the effect that a flow of water charged with debris must necessarily develop for itself that form of section that will give it a "maximum debris-carrying capacity" is an invalid generalization because it ignores erodibility of the banks; the influence of this factor increases with increase in slope and caliber of debris. The cross-sectional form developed by a stream may be "stable" in that it is not subject to modification as long as conditions remain the same, but "stability" in section is no guarantee of maximum efficiency for transportation. There is no need to labor this point with examples; it suffices to say that in many instances on record, efficiency for transportation in streams and canals has been greatly increased by artificial modification of self-adopted sections.

ADJUSTMENT IN SECTION IN THE SHIFTING CHANNEL

The tendency for erosional widening along both banks in the straight channel is, in the curving channel, localized and greatly accentuated at the outside of the curves. Whatever the type of meandering involved (Melton, 1936), the inner parts of the curving channel are bar-ridden shoals if the meanders are actively shifting. The meandering channel is usually deepest at the outside of the curves, but even here, if lateral shifting is rapid and the subjacent materials are resistant, the channel does not continue to operate in one place long enough to permit deepening to the potential depth of flood-stage scour. If outward shifting were stopped and if the shallows were filled so as to concentrate the flow in a narrowed channel, deepening would result. Efficiency for transportation would be further increased if the tortuous curves of the channel were smoothed.

The first point to be made, then, is that lateral shifting is one of the most important factors responsible for the inefficiency of the natural channel. This holds for the meandering stream, and it is true also for the braided stream. In general, efficiency for transportation varies inversely with the rate of lateral shifting.

The second point is that, other things being equal, the rate of lateral shifting in the graded stream increases with velocity and load; high-velocity, gravel-carrying streams on piedmont slopes of semiarid mountains shift laterally far more rapidly than low-velocity, silt-carrying streams of humid lowlands.

Consider now how a meandering stream will react to a change in controlling conditions, as for example, an increase in load. The engineer might be able to accommodate the stream to the increased load by artificially increasing the efficiency of the channel without increase in slope. Under natural conditions there will usually be both change in the channel characteristics and increase in slope. The increase in slope will be effected automatically by aggradation, and aggradation will continue until the slope is steep enough to provide the velocity required to transport, with available discharge and the prevailing channel characteristics, *whatever they may be*, all the debris delivered to the stream. Modification of the channel characteristics, considered separately as a mechanism of readjustment, will, on the other hand, be self baffling because increase in velocity required by increase in load will itself entail an increase in lateral shifting which will, in turn, tend to decrease the efficiency of the channel, and hence the velocity of the stream.

A graded stream may react to an increase in load by a more drastic change in the channel characteristics, namely, by a change from a meandering to a braided habit. Braiding involves the choking of each functional channel by bar building; the resulting maze of shifting minor channels has a total overall proportionate depth much smaller than that of the corresponding meandering channel. Here again, the effect on velocity of a change in the channel characteristics is precisely the reverse of that called for by the original change in external controls. Eventual readjustment to the new conditions (including increased load *and* notably decreased channel efficiency) will be achieved by increase in slope effected through aggradation.

These examples are certainly not intended to establish a general rule to the effect that, with a change in control, channel characteristics necessarily shift in a manner opposite to that required to bring the stream into balance with the new conditions. In some instances the effects of changes in the channel characteristics may be negligible, and in other instances they may contribute notably to the readjustment. But the examples do serve to bring out a basic difference in the role of adjustments in section and adjustments in slope in the equilibrium of grade; while adjustments in section may or may not accommodate the effect of a change in control, slope is always modified, by the stream itself, in such a manner as to absorb the effect of the stress. This relationship, the tendency for one of a number of partly interdependent variables to act as the outstanding counterbalance in effecting a readjustment to new conditions, is familiar in many types of equilibria. In the case of grade it means simply that the stream normally reacts to a change in controls calling for an increase or decrease in energy required for transportation by increasing or decreasing the total energy through modification of slope rather than by effecting economies in the energy dissipated in friction. A graded stream is a system, prodigiously wasteful of energy at every bend and shoal, kept in a constant state of balance under stable conditions, and brought back into balance after any change in controls, primarily by appropriate adjustments in slope.

EFFECT OF VARIATION IN CHANNEL CHARACTERISTICS ON THE GRADED PROFILE

It has been indicated that changes in ratio of load to discharge, in caliber of load, and other factors, occur in the graded stream, and that, while none of these changes

is necessarily systematic, they usually combine to cause a downvalley decrease in the slope of the profile. Variation in the channel characteristics from segment to segment under stable conditions is due, in part directly, to changes in these other factors—for example, decrease in the caliber of the load that is moved along the stream bed tends, other things being equal, to be accompanied by an increase in proportionate depth. But changes in the channel characteristics are due largely to change in the resultant of these other factors, namely, velocity, and, in turn, rate of lateral shifting. The paragraphs below are intended to show the nature of the changes that may be expected in an ideal case and how these will affect slope.

In the upper parts of the graded stream,[5] velocity, and therefore the power of the stream to cut laterally, is high, but the valley floor does not greatly exceed the width of the stream itself, and the rate of lateral shifting is inhibited by confining rock walls. In the absence of well-developed meanders, the channel is relatively straight. For these reasons the actual rate of lateral shifting in any representative segment is relatively slow, and the proportionate depth relatively large.

The middle parts of the graded stream are characterized by fully developed meanders and by decreased velocity and therefore decreased corrasive power. But the actual rate of lateral shifting may be increased because the tendency for lateral shifting increases with decrease in the radius of curves, and especially because the stream now operates largely in unconsolidated alluvium on a wide valley floor. Other things being equal, proportionate depth decreases with increase in the rate of lateral shifting.

Finally, in the lower parts of the stream, velocity and corrasive power may decrease until there is a notable decrease in the rate of lateral shifting even in alluvial materials, with a corresponding increase in proportionate depth. Degree of sinuousity of the channel may remain the same (as in the middle parts) or may decrease.

It follows from the earlier discussion that, in the measure that these changes in the channel characteristics affect velocity, they will result in departures from the theoretical profile adjusted to discharge and load, but with uniform channel characteristics throughout. The effect will be to decrease the slope required to provide the velocity needed for the transportation of load with available discharge in the upper parts, to increase the slope required etc., in the middle parts, and to decrease the slope required etc., in the lower parts.

Deductions as to the effects on slope of the contrasts between the upper and middle sets of conditions are verified by relations described by Gilbert on the Yuba River in California:

"Where the Yuba River passes from the Sierra Nevada to the broad Sacramento Valley its habit is rather abruptly changed. In the Narrows it is narrow and deep; a few miles downstream it has become wide and shallow. Its bed is of gravel, with slopes regulated by the river itself when in flood, and the same material composes the load it carries.

[5] The terms "upper", "middle", and "lower" are used here for convenience to designate contrasted sets of conditions that bear on actual (not potential) rate of lateral shifting of a graded stream. These contrasted sets of conditions usually occur in the geographic order suggested by the terms, but depending on the geology of the drainage basin, they may occur in any order along the part of the stream that is graded. The terms should not be confused with the upper (downcutting), middle (cutting and filling), and lower (upbuilding) parts of the overall profile recognized by many workers. These subdivisions of the profile as a whole are discussed later; they have no place in the present treatment of factors bearing on the graded slope.

"In the Narrows the form ratio during high flood is 0.06 and the slope is 0.10 percent. Two miles downstream the form ratio is 0.008 and the slope is 0.34 per cent. Thus the energy necessary to transport the load where the form ratio is 0.008 is more than three times that which suffices where the form ratio is 0.06; and it is evident that the larger ratio is much more efficient than the smaller" (Gilbert, 1914, p. 135).

Gilbert's "form ratio" is depth over width; it increases with increase in proportionate depth. While Gilbert does not say so, the abrupt change in depth-width relations on the Yuba is associated geographically with, and is certainly due in large part to, a change from a relatively low rate of lateral shifting in the rock-walled "Narrows" to a rapid rate of shifting on the piedmont alluvial plain. This downvalley *steepening* in slope at the point where a stream issues from a gorge is precisely the reverse of what we normally expect, and it is the reverse of what we usually find, because decrease in caliber of load, loss of water through infiltration and evaporation, and other factors, usually outweigh the effects of lateral shifting on channel characteristics and of channel characteristics on slope.

Factual relations at other California canyon mouths described by Sonderegger (1935, p. 296–300) indicate that the Yuba is not an isolated case; Sonderegger's reasoning as to the cause of the slope contrasts corresponds closely with that advanced here. These examples were not known to the writer when the deductions were set down in their present form—the examples therefore are "verification", by prediction of extraordinary or unique relationships, of the theory from which the deductions were drawn.

The effect of rate of lateral shifting on channel characteristics, and, in turn, of channel characteristics on slope in the middle and lower sets of conditions is strikingly illustrated by the Illinois River. This stream seems to exemplify the logical climax or end stage of the hypothetical sequence of downvalley changes in slope and channel characteristics outlined above.

According to Rubey the lower Illinois channel does not shift perceptibly, is much narrower but somewhat deeper than that of the adjacent part of the Mississippi, and is deepest at the inside rather than at the outside of its bends. The river has a slope of less than 2 inches per mile, actually lower than that of the Mississippi from Memphis to the Gulf.

An explanation of the remarkable habits of the Illinois, taken in part from Rubey's writings (Rubey, 1931a and the unpublished report mentioned earlier) and in part rationalized from factual relations described by him and shown on the topographic sheets, is as follows: The river flows in a valley formed by a much larger stream which served as the outlet of Lake Michigan during late-glacial times. Now, after several hundred feet of aggradation due in part to post-glacial aggradation of the Mississippi (which it enters), the lower Illinois is neither aggrading nor degrading at an appreciable rate. It is essentially graded (Rubey, 1931a, p. 366) and, as such, has a velocity adjusted to the transport of all of the debris shed into it. The slope of the stream is, in other words, adjustee to the present load under the prevaling conditions. The main stream is partly or wholly laked above the mouth of the Sangamon at Beardstown, and minor lateral tributaries below this point supply little coarse clastic debris. Under these circumstances the velocity required for transportation of the debris handled by the Illinois below Beardstown is very low—so low, in fact, that inertia fails to counteract the tendency of the principle current to follow the shortest and steepest route, which, in all curving streams, lies along the *inside* of the bends. This introduces a new factor tending to inhibit or halt lateral shifting (which would be very slow in any case because of low velocity) with the result that the stream maintains a relatively narrow and deep channel. The efficiency of this channel is so great, relative to that of actively shifting streams, that the Illinois develops the velocity required for the transportation of the load supplied to it on an exceptionally low slope.

The characteristics of the Illinois River are due largely to fortuitous circumstances (glacial drainage diversion, etc.), but the same type of regimen is approached in the lower flat reaches of many streams. Flattening of slope in the lower reaches is, for example, accompanied by a decrease in the rate of lateral shifting and an increase in proportionate depth on the Mississippi River (*see* Humphreys and Abbott, 1876, p. 107, 122) and the Brazos River in Texas (Barton, 1928, p. 622). It seems likely that this type of regimen, exceptional during the present epoch of crustal unrest and high-standing continents, may have been during earlier geologic periods a prevalent type in the lower parts of sluggish trunk streams draining areas of exceedingly low relief in the penultimate stages of the Davisian cycle of erosion.

LOCAL VARIATION FROM MEAN SLOPE

Detailed surveys based on reading of closely spaced gauges at the same river stage usually reveal what may be called local variations in the slopes of graded streams. These local departures from mean slope in any short segment may be fixed in position over a period of years, or they may shift along the stream; they usually vary in position with variation in discharge. They are in most cases clearly related to local variations in proportionate depth or detailed roughness, or to sharp bends, split channels, and other irregularities in trend which increase frictional retardation of flow. The fact that some of the local variations are obviously not associated with changes in load has led one student of streams to publish this rather remarkable nonsequitur: "the declivity of the adjusted stream is not a function of load". The fact is, of course, that declivity is not controlled by load alone.

These local variations in slope merit only brief mention here for the same reason that seasonal variations in discharge, velocity, and load were left largely out of account in the discussion of equilibrium relationships. Local changes in slope of the water surface, as such, are usually symptoms of some local "defect" in the channel; from the point of view of the geologist they are usually negligible because they are not reflected in the slopes of the valley floors produced by streams.

BACKWATER AND DRAW-DOWN EFFECTS

The usual downvalley decrease in the slope of the graded stream has led to the suggestion that the profile tends to be asymptotic with respect to a horizontal plane passing its base level. Similarly, the profile of a tributary is sometimes supposed to approach the slope of the main stream near the junction. It will be shown later that in a special case (aggradation) there is such a tendency. But it is the essence of the concept of grade that declivity is controlled by velocity or energy requirements and, in the graded stream, base level, as long as it does not change, has no bearing on velocity or energy requirements. Base level controls the *level* or *elevation* at which the profile is developed, but it does not influence the *slope* of the profile. For this reason a generalization to the effect that the graded profile approaches base level asymptotically is not valid.

In detail, profile relations in the vicinity of downvalley control points (that is, either general or local base levels) differ markedly (1) where the stream enters still water, (2) where the downvalley control is the lip of a waterfall, and (3) where a

tributary enters a trunk stream. In (1) the lowermost part of the profile may show the "back-water effect" to a greater or less extent depending upon a number of factors; additional factors are involved if the "still water" is tidal, and/or if outbuilding of a delta is in progress. In (2) the lowermost part of the profile will show a "drawdown curve," that is, a steepening in the slope of the water surface resulting from a decrease in cross-sectional area due to acceleration in velocity toward the point of free fall. In (3) the backwater curve may affect either tributary or trunk stream or both depending upon their relative velocity and discharge and on the angle (in plan) between the streams at the confluence. These three different types of "base level" and their contrasted effects on a transitional zone in the lowermost part of the profile qualify the statement made in the last paragraph with respect to the relation of the overall profile to base level. But these relationships are local details having no direct bearing on the concept of grade.

EFFECTS OF DIFFERENCES IN ROCK RESISTANCE

Differential abrasion by streams tends to bring into relief differences in bedrock resistance; resistant rocks often form falls or rapids separating adjoining graded reaches. But if the stream be graded across the barrier, differences in bedrock resistance have no direct influence on its slope; theoretically and actually, as indicated earlier, graded streams cross belts of such contrasted rock types as quartzite and shale without change in slope at the contacts. Differences in the rock types traversed by the graded stream may, of course, cause changes in slope if associated contrasts in topography or lithology alter the amount and caliber of the load supplied to the stream, or if associated contrasts in valley-floor width affect rate of lateral shifting or details of trend or cross-sectional shape of the channel.

SUMMARY

The longitudinal profile of a graded stream may be thought of as consisting of a number of segments, each differing from those that adjoin it but all closely related parts of one system. Definition of the unit segment (in terms of length, permissible slope variation, etc.) depends on the purpose of the investigation.

Each segment has the slope that will provide the velocity required for transportation of all of the load supplied to it from above, and this slope is maintained without change as long as controlling conditions remain the same. The graded profile is a slope of transportation; it is influenced directly neither by the corrasive power of the stream nor bed rock resistance to corrasion.

Some changes from segment to segment in factors controlling the slope of the graded profile are matters of geographic circumstance that are not systematic in any way; these include the downvalley increase in discharge, and the downvalley decrease in load relative to discharge, that characterize trunk streams flowing from highland areas through humid lowlands. Other changes, as downvalley decrease in caliber of load by reason of attrition, may be more or less systematic between tributary junctions. Still others, as change in channel characteristics, are partly dependent on changes in load and discharge; the channel characteristics are determined chiefly by

caliber of load and rate of lateral shifting of the channel, and the rate of channel shifting is itself dependent on velocity and erodibility of the banks.

These changes are usually such as to decrease slope requirements in a downvalley direction but, because none of them is systematic, the graded profile cannot be a simple mathematical curve in anything more than a loose or superficial sense. We can proceed toward an understanding of the graded profile, not by "curve matching", but by rigorous analysis of adequate sets of data for unit segments of natural and laboratory streams numerous and varied enough to reveal the effect of variation of each of the factors separately. An essential prerequisite for efficiency in the gathering and analysis of the data is recognition of the difference between the graded profile that is maintained without change, and the ungraded profile that is being modified by upbuilding or downcutting.

RESPONSE OF THE GRADED STREAM TO CHANGES IN CONTROL

GENERAL STATEMENT

The response of a graded stream to any change in control is systematic in that it is predictable in terms of Le Chatelier's general law: "If any stress is brought to bear on a system in equilibrium, a reaction occurs, displacing the equilibrium in a direction which tends to absorb the effect of the stress." This section outlines the manner in which a graded stream, as a system in equilibrium, reacts to "stresses" by considering the nature of its response to changes in some of the controlling conditions which were, in the preceding section, held constant.

The method of presentation adopted to some extent above but used more particularly here involves deduction, from the general concept, of specific reactions that should be expected as results of a number of changes in control, and the matching of these "expected consequences" with field examples. This method of testing the theory is neither superior nor inferior to the laboratory model method; it is simply different from the experimental method which it supplements but certainly cannot replace. Its validity as a test depends on (1) whether the deductions are logical, (2) whether the effects are specifically related to the stated causes, and (3) whether the examples are representative. Obviously, in some cases, the reasoning is inductive; the deductive method of presentation (Johnson, 1940) is not followed rigorously in most of these instances. But it is worth nothing that many of the reactions were in fact predicted purely on the basis of deduction, and later verified by reference to the record, and that a survey of factual relations set forth in the literature has failed to discover any effect of a given cause that does not fit the concept.

Examples are not cited, or are mentioned briefly, where relationships are clear cut or generally familiar. In some instances scores of examples bear out the deductive analysis, each differing from the others in nice detail; some selection was therefore necessary. In general, examples were selected in which a given cause can be related to a definite effect with the least explanatory argument. If alternative examples occur to the reader that illustrate a point more clearly than those cited, that is good; if, on the other hand, there are cases that fail to conform to the general thesis a description of them will be a contribution to our understanding of streams.

Engineering examples are usually intended to show the almost telegraphic rapidity with which preliminary reactions are propagated upvalley and/or downvalley from the point where a change has been introduced by man; some of the geologic examples show the nature of the response to analogous natural changes over a period of time in which more or less complete readjustment may be attained.

Discussion in the paragraphs below is confined to the general mechanism by which readjustment is effected. Contrasted methods of aggradation, the bearing of certain secondary cause-and-effect couples on the slope of the final readjusted profile, and the contrast between the form of the adjusted (or readjusted) profile of the graded stream and the disadjusted profile of the aggrading or degrading stream are treated later.

INCREASE IN LOAD

A once-graded stream responds to an increase in load primarily by steepening its declivity below the point of influx. The steepening is accomplished by deposition of part of the excess load in the channel at the point of influx with a consequent upbuilding of the channel at that point and the formation of a steepened part immediately below.[6] Steepening of any segment permits increased transport of load through that segment to the next segment which is in turn the site of deposition and steepening. Thus the effect of an increase in load is registered by the downvalley movement of a wave of deposition, large or small depending on the rate and manner of addition of the load, and deposition must continue throughout the stream below the point of influx until the slope is everywhere adjusted to the transport of all of the debris delivered to it.

The classic example of marked and immediate response of streams to increase in load associated with works of man is the aggradation and resulting widespread destruction of agricultural lands along the eastern side of the Great Valley of California caused by hydraulic mining on the western slopes of the Sierra Nevada between 1855 and 1884, when court decisions halted discharge of mining debris into the Sierra streams (Gilbert, 1917). Various surveys to 1894 are summarized as follows:

"the deposit . . . was 20 miles long, had a maximum width of three miles, covering 16,000 acres and containing 600,000,000 cu. yd. It was 20 feet deep at the river's mouth, 35 feet deep at the edge of the foothills, and 80 feet deep 5 miles higher up on the Yuba River. The grade of the original bed was 5 feet per mile. After the fill was made, the grade per mile was 2½ feet at the mouth, 10 feet at the middle zone, and 20 feet on the upper reaches" (Waggoner, in discussion of Stevens, 1936, p. 271).

The effect of increase in load due to natural causes is most strikingly exemplified by the aggradation that commonly occurs when river valleys are invaded by glaciers. Automatic steepening of the declivity of the proglacial stream is not necessarily proof that great additional *quantities* of debris are being shed into them. The detritus carried from upvalley and delivered to the stream at the terminus of the glacier is usually much coarser than that formerly delivered to the same point from upvalley by running water, and increase in caliber may be more important than increase in quantity of load as a cause of the profile steepening.

[6] A stream affected by a change in controls of any type "deposits part of its load" or "picks up more load" by appropriate modifications in the amount of material deposited and picked up in the course of its normal seasonal fluctuations, and the net differences are usually very small compared with the great bulk of material moved and relaid during these fluctuations.

Because glaciation is usually a relatively brief episode in the life history of the drainage basin, with the main cycle of advance and recession interrupted by numerous minor pulsations, and with continual change in topographic relations governing discharge of water and debris from the ice front, proglacial streams rarely or never attain adjustment. Their profiles therefore differ from the more or less completely adjusted pre-glacial and post-glacial profiles not only in overall slope, but also in form. (*See*, for example, MacClintock, 1922, p. 575, 681.)

DECREASE IN LOAD

A decrease in load may be thought of as occurring at any point in the stream. It may be stated for the time being that the stream simply makes up for deficiency in the load supplied from above by picking up additional load from its channel floor. The net result is downcutting, with a consequent lowering in declivity downvalley from the point where the change occurred. Downcutting must continue until the profile is reduced to that slope which will provide just the velocity required to transport the reduced load.

Because of the operation of the reservoir as a settling basin, the dam is the most common man-made cause of decrease in load. The downcutting that may result is typically shown by the Rio Grande below the Elephant Butte Reservoir and the Colorado below Lake Mead (Stevens, 1938) the Saalach River below the Reichenhall Reservoir (Schoklitsch, 1937, p. 157) and in many other cases (Lane and others, 1934). This effect of decrease in load due to damming is almost always complicated by elimination of peak discharges and velocities that results from the use of the reservoir as a water storage basin.

Terraces cut in earlier fill characterize Pleistocene outwash plains and valley trains. The usual downvalley convergence of terrace profiles cut during the period of deglaciation is probably due primarily to decrease in caliber of load reaching any given segment of the degrading stream as the distance between that segment and the receding ice front increases.

Davis (1902, p. 261) treated the very gradual decrease in stream slope that results from decrease in load due to reduction in relief during the humid erosion cycle; Johnson (1932) and others described analogous effects around the borders of shrinking desert ranges.

CHANGES IN DISCHARGE

If a segment of a graded stream receives all or most of its load at the upper end, changes in discharge call for readjustments in the slope in much the same way as changes in load. A decrease in discharge requires an increase in declivity because the load, remaining the same, must move faster through a smaller cross section, and because, as indicated earlier, decrease in the cross-sectional area of the channel involves a relative increase in frictional retardation of flow and, hence, a decrease in velocity. The stream affected by a decrease in discharge, being unable to transport all the load supplied to it on its former slope, deposits some of the load and thereby steepens the slope, the process continuing until the reduced stream is able, by reason of increased velocity on the steepened slope, to transport all the load shed into it. The opposite adjustment occurs in the case of increased discharge.

A special case of the operation of this principle is described by Salisbury (1937) in the lower Mississippi Valley. Subsequent to diversion of part of the Mississippi discharge into the Atchafalaya channel in 1882 there has been, downvalley from the point of diversion, silting of the bed of the reduced Mississippi, and lowering of the slope of the augmented Atchafalaya. Clearing of rafts on the Red River (the upper Atchafalaya), confinement of both the Mississippi and the Atchafalaya be-

tween levees, and other works of man have altered the regimen of both streams since the diversion. For these reasons, and particularly because of the exceedingly low slopes of the streams involved, the effects of the diversion are revealed only by careful evaluation of the evidence by Salisbury (chiefly in terms of variation in gauge heights) and by Lane (in discussion of Salisbury's paper, chiefly in terms of variation in discharge).

The distance from the point of diversion to the Gulf is about 125 miles along the Atchafalaya, and about 310 miles along the Mississippi. Deterioration of the discharge capacity of the Mississippi channel since the diversion began and concomitant increase in discharge through the steeper Atchafalaya suggest that we are viewing a type of deltaic drainage change, set in motion in this instance by man, which must have occurred repeatedly in the past under natural conditions. Salisbury's demonstration of silting in the trunk channel below the diversion provides an explanation of a mechanism by which deep-channel, slow-shifting streams like the Mississippi may transfer themselves to different radial positions as delta growth proceeds.

The principle and the general mechanics of readjustment are precisely the same in the more general case of a main stream which receives notable additions of debris from tributaries, but the effects on the form of the profile may be very different because loss of discharge in the main stream calls for local readjustments of slope at each tributary junction, usually enough steepening to permit the reduced main stream to transport the load supplied by the tributaries.

Aggradation of the trunk stream at and below tributary junctions is now in progress on the Rio Grande and the Colorado River below the Elephant and Boulder dams, due chiefly to elimination of peak discharges that formerly moved detritus delivered to the main channel by flash floods on the tributaries (Stevens, 1938). In these cases the effect of reduction of peak discharges locally outweighs the general tendency for downcutting due to retention in the reservoir of the bed load supplied from the upper parts of the trunk stream.

Recent widespread incision of valley floors by streams in the Southwest is ascribed by Bryan (1925; 1940) and Bailey (1935) to increase in peak discharge resulting from an increased rate of runoff due to reduction in vegetative cover. Assuming that this diagnosis is correct, whether the cause be climatic change (Bryan) or overgrazing (Bailey) the recent arroyo cutting is of special interest because, as in the examples last mentioned, a change in distribution of discharge through the year produces effects similar to those caused by a change in discharge, and because the downcutting, a preliminary result of deterioration in vegetative cover, may revert to upbuilding when and if increased load resulting from accelerated erosion of the denuded slopes begins to affect the streams.

The most common geologic cause of decrease in discharge is drainage diversion, and the most evident effect is the growth of side-stream fans in the valley of the reduced stream. The classic case is the partial blocking of the valley of the Petit Morin after capture of its headwaters by the Marne and the Aube; the marsh of St. Gond was caused by detrital accumulations which locally reversed the slope of the valley of the Petit Morin (Davis, 1896, p. 603, 604). Local slope reversals on a larger scale are represented by Lake Traverse and other lakes in the valley now occupied by the Minnesota River; this small postglacial stream has been unable to maintain the low-gradient valley cut during the Pleistocene by the very much larger "Warren River", which served as the outlet of Glacial Lake Agassiz. The final step in the blocking process is illustrated by an enormous accumulation of tributary fan detritus, possibly as much as 700 feet thick, in the gap cut by the former Shoshone River through the Pryor Mountains in Montana; in this case the discharge of the Shoshone was so greatly reduced by headwater diversion that the direction of flow of the beheaded trunk stream was completely reversed by tributary fans (Mackin, 1937, Fig. 6).

It appears, therefore, that reduction in discharge in a trunk stream joined by tributaries tends in general to cause profile changes that express the increased relative importance of the tributaries in the economy of the drainage system, and that, depending on how drastic is the reduction of the trunk stream, and how vigorous the tributaries, the main stream may respond by appropriate modification of its profile during a period of disadjustment or may disintegrate into a series of lakes and reversed segments.

RISE OF BASE LEVEL

A rise of base level is equivalent to the rising of a barrier across the path of the graded stream. Each unit of increase in the height of the barrier tends to flatten the declivity immediately upstream. The stream, unable because of decreased declivity to carry all of the load through the flattened segment, deposits in the segment, thus increasing the declivity and transferring the flattening upvalley. Continuation of the process results in upstream propagation of a wave or, better, of an infinite number of small waves of deposition.

If the barrier is raised slowly the stream may maintain itself in approximate adjustment during the process; its rate of aggradation is determined by the rate at which the barrier is elevated. If the barrier is raised rapidly or instantaneously a lake is formed; the distal part of the delta is then the "flattened part" of the profile, and the rate of aggradation is determined by the rate of delta building into the lake. In either case the successive profiles developed during the period of readjustment will differ markedly in form from the original profile and from the eventual completely readjusted profile. The final readjusted profile will tend toward parallelsim with the original profile, differing in this respect from the cases treated above. But, because of secondary effects of aggradation to be discussed later, precise parallelism will usually not be achieved; the only generalization that can be made is that the new profile will be everywhere adjusted to the new prevailing conditions.

Rapid upvalley propagation of a wave of deposition due to rise in base level is well shown by profile modifications brought about within a few years by erection of Debris Barrier #1 on the Yuba River (Gilbert, 1917, p. 52–63); Gilbert's figure 7 illustrates the typical wedging out upstream of the preliminary detrital accumulations. (See also Sonderegger, 1935, Fig. 2, p. 298).

The same effect, but on a much larger scale, is seen in aggradation on the Rio Grande above the Elephant Butte Reservoir (Eakin and Brown, 1939, p. 90–99). At San Marcial, a town near the head of the reservoir, the channel of the Rio Grande has been raised at least 10 feet since 1916, when the reservoir was completed, and the town site is largely buried in silt. Blaney states that surveys made in 1934 show a rise of the channel of 7 feet since 1918 at La Joya, and 2 to 4 feet at Albuquerque (Blaney, in discussion of Stevens, 1936, p. 266). La Joya and Albuquerque are about 50 and 100 miles (airline) above San Marcial, respectively, and Albuquerque is 500 feet above the level of the reservoir.[7]

The Elephant Butte Reservoir is about 40 miles long and the spillway crest is 193 feet above the original river bed. A statement to the effect that the eventual readjusted profile of the Rio Grande, long after complete filling of the reservoir, will be parallel with the original river bed and about 200 feet higher is, of course, wholly indefensible. It is, however, probably closer to the truth than the comfortable assumption that the final debris fill will wedge out to zero within a few tens of miles above the original head of the reservoir. The profile of the aggrading Rio Grande during the period of disadjustment will be less steep than the original profile, but the final readjusted profile may be less steep or steeper. It is not necessary to look so far into the future for trouble—a few tens of feet of upbuilding to the latitude of Albuquerque would destroy highways and railways, towns, irrigation works, and farmlands with an aggregate value that may exceed the cost of the dam.

[7] Stafford C. Happ points out (personal communication) that increased sedimentary loads of tributaries in the last 50 years have probably caused aggradation in the Rio Grande Valley independently of the influence of the Elephant Butte Reservoir. If quantitative evaluation of adequate data indicate that all of the upbuilding noted by Blaney at La Joya and Albuquerque is due to these "upvalley" influences it will mean simply that the effects of the reservoir have not yet reached these points. For definite evidence that aggradation had extended to a point at least 15 miles above the reservoir by 1941 see Happ, in discussion of Stevens (1945, p. 1298).

Aggradation of the Kickapoo River in Wisconsin is ascribed by Thwaites and Bates chiefly to Pleistocene upbuilding of the Wisconsin River, which it enters; it is in effect, therefore, a case of aggradation caused by a "geologic" rise of base level. As in all such cases, aggradation undoubtedly altered conditions controlling slope on the Kickapoo; it is interesting, nevertheless, to note that the modern profile for the first 100 miles above the mouth corresponds closely in slope with the original profile determined by well logs (Bates, 1939; Thwaites, 1928, p. 628).

In some respects analogous to the more or less adjusted Kickapoo and serving especially as an antidote for any idea that the readjusted stream *must* be less steep than the original stream is the striking case of aggradation above a debris barrier on the Bear River in California; the approximately adjusted profile of this river above the barrier is notably steeper than the original profile of the stream (Stevens, 1936, p. 219).

Johnson and Minaker (1945, p. 904) cite an unpublished report by Kaetz and Rich to the effect that study of profiles above 22 debris barriers shows that the slopes of the deposits average from 37 to 49 per cent of the original slope—these cases are recognized as not having reached "equilibrium conditions". They state further that in model studies slopes up to 90 per cent of the original streambed slopes were obtained. Their interpretation of the difference in the form of the original profile and the profiles developed during aggradation differs in detail from those advanced later in the present article, but their factual data, reasoning, and conclusions conform in all respects with the general theory of grade.

Loss of storage capacity by silting is one of the outstanding engineering problems of the century; the problem is many-sided, and the literature is extensive. (*See*, for example, Brown, 1944; Stevens, 1936, 1945; Witzig, 1944; and papers cited therein.) Two practical implications of the theory of grade bearing on special aspects of the problem follow so directly from the views and factual relations cited above as to merit brief mention in passing.

It seems to be common practice to determine the "useful life" of a reservoir (usually the time required for filling with debris to spillway level at the dam, but varying depending on the purpose of the reservoir) by dividing the yearly increment of debris into the capacity of the reservoir for water, with due allowance for compaction and related factors. This method is evidently based on the tacit assumption that, when the delta front has advanced any considerable distance toward the dam, the river will carry its detrital load from the original head of the reservoir to the delta front on a surface of no slope (i.e., the water level). Mere statement of this basic assumption in these terms demonstrates its absurdity. Remedial measures costing large sums are in part contingent on predicted rates of storage depletion; these predictions, particularly on high gradient streams carrying a coarse bed load, are subject to gross errors when they fail to take into account the progressive increase in the proportion of the stream's load that is deposited on the valley floor above the reservoir as aggradation proceeds. (*See* Eakin and Brown, 1939, p. 6, 7; Happ, in discussion of Stevens, 1945, p. 1298–1300.) Research on what may be called "the form of the aggrading profile" is much needed, and the results must of course be quantitative to be useful. It is the writer's conviction that some qualitative understanding of the complex interrelationships of the factors at play in aggrading streams is the essential prerequisite for such quantitative studies if they are to yield general "laws" rather than a set of empirical constants of the type that lead some engineers to conclude that each individual stream has its own rules of conduct.

Study of the form of the aggrading profile may be expected to pay dividends not

only by increasing accuracy of the storage depletion rate but also by developing methods by which the rate may be decreased. As indicated especially by the soil conservationists (Brown, 1944), a basic part of any comprehensive attack on the silting problem is reduction insofar as practicable of the debris shed into streams from uplands in the drainage area. The next step is to decrease the load delivered by the streams to the reservoir; the trend of thought in this connection seems to favor use of debris dams. But another method of holding debris out of the reservoir merits more attention than it has received. Normal upvalley aggradational processes may be accelerated by use of groins and other temporary and inexpensive structures so placed as to cause the stream to decrease its transporting efficiency (perhaps it would be better to say—so placed as to accentuate the natural tendency of the meandering or braided channel to be exceedingly inefficient). This method conforms with the well-recognized principle that, in dealing with rivers, better results may be achieved with less human effort by working with the water, rather than against it; river training to induce deposition is to impounding debris by damming as river training to maintain a navigable channel is to dredging. Training measures intelligently planned to increase the rate of upbuilding of the channel by deposition of bed load, and to increase the rate of vertical accretion on the floodplain by overbank deposition of suspended load, combined with suitable types of agricultural utilization of the valley floor as upbuilding proceeds, may provide a partial answer to the problem of reservoir silting. Quantitative data are needed to evaluate the practicability of controlled upvalley aggradation as alternative or supplementary to the debris dam system.

These suggestions apply to the simple case (as that of Lake Mead on the Colorado) where protection of the reservoir is the primary concern. The situation is quite different on the Rio Grande, where aggradation above the Elephant Butte reservoir will destroy valuable property on the valley floor. The engineer charged with corrective measures on the Rio Grande will face an interesting dilemma. He can, by increasing the efficiency of the channel, permit the stream to transport its load on a lower slope, thus delaying destruction of upvalley property and shortening the useful life of the reservoir, or he can, by decreasing the efficiency of the channel, force the river to develop a higher slope by aggradation, thus hastening destruction of upvalley property and lengthening the life of the reservoir.

LOWERING OF BASE LEVEL

Lowering in base level, is, insofar as the response of the stream is concerned, essentially the same as the lowering of a barrier in its path. Each small lowering of the control point steepens the gradient immediately upstream. Accelerated velocity in the steepened portion results in downcutting, and the steepening is propagated upvalley. Downcutting must continue until the slope is again completely adjusted to supply just the velocity required to transport all of the debris shed into the stream; as in the last case, and with the same qualifications, the final readjusted profile will tend to parallel the original profile.

A man-made change which corresponds with a lowering in base level is the local shortening of a stream by the elimination of meander loops; the general trend of the upvalley effects is indicated or,

better, merely suggested by changes in the profile of the Mississippi River brought about by a series of artificial cutoffs and other channel improvements between 1929 and 1939. A generalized and more or less diagrammatic profile (Ferguson, 1939, p. 829) shows the new slope between the cutoffs essentially the same as the original slope, the changes in level resulting from the individual cutoffs being cumulative in an upvalley direction. At Arkansas City, at the head of the cutoffs, the river level was lowered about 15 feet. The effect was noted in 1939 at a gauge 107 miles above the head of the cutoffs, where there was a lowering of 2 or 3 feet in flood stage. The river has certainly not yet adjusted itself to the new conditions; the chief significance of the recorded profile changes to date is the sensitiveness of the stream to "lowering of base level", and the extremely rapid headward progression of the first effects of that lowering.

[Macar, on the basis of studies of natural cutoffs in European and American rivers, concludes that the "steepened part" caused by a given cutoff moves headward in large streams several hundred times faster than the rate of downcutting of the stream; his profiles show subparallelism between the original and readjusted slopes (1934).

CLASSIFICATION OF CHANGES IN CONTROL

Changes of the type discussed above may be usefully divided into two catagories: (1) "upvalley", and (2) "downvalley" changes in controls; the terms are used, of course, with reference to a particular segment under consideration. As indicated in an earlier section the slope of the graded profile is determined primarily by load and discharge, which are "upvalley" factors; change in either or both of these factors calls for changes in *slope*. The level at which the profile is developed is determined by base level, which is a "downvalley" factor; change in base level calls for a change in the level of the profile but does not, directly, call for change in its slope. A single change usually affects the stream differently above and below the point where the change occurs; for example, if the load delivered by a tributary is greatly increased the effect on the trunk stream below the junction is increase in load, and above the junction rise in base level. The distinction between upvalley and downvalley changes in control is of special importance in interpreting the significance of parallel and converging terrace and valley-floor profiles.

Crustal movements, as tilting or warping of any segment of a graded stream, constitute a third category of changes. Such changes are neither upvalley nor downvalley, and they do not necessarily involve changes in load, discharge, or base level; they simply cause a forcible distortion of all earlier developed terrace and valley-floor profiles within the segment affected. The stream responds by building or downcutting or both. Except insofar as base level or factors which control slope are changed, either in consequence of the crustal movements directly or by reason of the upbuilding or downcutting of the stream, the completely readjusted profile will be developed at the same level and will have the same slope as the original profile.

REGRADING WITH PROGRESS OF THE EROSION CYCLE

A stream may lengthen during its life history by headward erosion, delta growth, and the development of meanders. Lengthening by the slow extension of ungraded headwaters and by capture involves additions of discharge and load to the stream. The contrasted effects of these additions have been treated earlier; their net effect on the graded portion of the stream is determined by their relative importance. The

change, with the progress of the erosion cycle, from the relatively straight course of youth to the meandering course of maturity involves a systematic lengthening of the stream. This lengthening, together with that resulting from delta building, tends to decrease declivity and hence calls for aggradation to maintain the slope required for the transport of load. Whether aggradation will actually occur and how far upvalley its effects may be felt at any stage depends upon the relative rate of an accompanying opposed upvalley change, namely, the tendency for slow lowering of graded declivity resulting from decrease in load with advancement of the cycle. Green has developed an interesting mathematical treatment of the change in the form of the profile by which, with certain initial assumptions made, the past and future shifting of the zones of aggradation and degradation can be determined (Green, 1936; *see also* Miller, 1939; Lewis, 1945).

These changes may be difficult or impossible to detect in large, low-gradient streams of humid regions, especially because they tend to be masked by or confused with the effects of subsidence in the deltaic area and eustatic changes in sea level. Their effects are more clearly seen in high-declivity graded streams flowing from semiarid ranges to closed desert basins under such conditions that base level is raised *pari passu* with decrease in the declivity of the stream that accompanies reduction of the range. As shown by Johnson and others, the stream maintains its graded condition under these conditions by *regrading*, being engaged in aggradation in the lower levels at the same time that it is degrading on the rock-floored pediment, the line of demarcation between the contrasted zones shifting rangeward or basinward depending on the relative importance of the downvalley and upvalley factors (Johnson, 1932).

There is perhaps nothing seriously wrong with the statement that the stream maintains a graded condition while continuously lowering its slope during the process of the cycle of erosion; the statement is merely an oversimplification that is confusing because it is inconsistent. In a textbook discussion of the *cycle of erosion* it would seem preferable to state that, having developed an equilibrium slope under existing conditions at any given stage of the cycle, that is, having attained a condition of grade, the stream must continually alter its slope and its graded condition as controlling conditions change. The rate of change in controlling conditions is exceedingly slow, and the stream's adjustment to the controlling conditions is exceedingly delicate. The lag between change in conditions and adjustment is therefore so completely negligible that, viewed at any one time, the stream may be properly regarded as being graded. But if attention is focused on the orderly change in landforms during the erosion cycle, that is, *if the topic under discussion is the cycle*, then the emphasis should be not on the "static" equilibrium at any one time, but on the gradually shifting equilibrium over a long period of geologic time. In the course of the erosion cycle the stream maintains itself, not in any one graded condition, but in an infinite number of different graded states, each differing slightly from the last and each appropriate to the existing conditions.

If there is anything paradoxical or confusing in this relationship it escapes the writer. But even the best student may be hopelessly confused if the concept of grade and the wholly different concept of the erosion cycle are churned up together and administered in one dose. Grade must be explained in terms of channel processes

and thoroughly understood as a condition of equilibrium in the stream as a transporting agent before the fourth dimension, geologic time, is introduced in a consideration of the role of the stream in the cycle.

An understanding of grade is essential for any theoretical analysis of the erosion cycle, but the principle geologic application of the concept is in interpretation of erosional and depositional landforms produced directly by the work of streams. The field worker in most continental areas finds that he must deal with streams that have at different times in the recent past engaged in episodes of downcutting and valley filling, both proceeding at varying rates and punctuated by pauses. The complex history of most modern stream valleys is undoubtedly due largely to the climatic fluctuations, crustal movements, and eustatic changes in sea level that characterize the Pleistocene. Valley floors and terrace remnants of several types and with various slopes in the same valley record the automatic tendency of the streams to adjust themselves to these changing conditions; even if equilibrium were never attained the theory of grade would be indispensable for any understanding of these strivings toward it. But, as shown by examples cited earlier, which could be multiplied a hundred fold, essential equilibrium is in fact often attained and maintained long enough for the production of distinctive landforms by long-continued lateral planation at the same level.

SHORT-TERM CHANGES

After the meandering habit is fully developed in any segment the length of the stream is not significantly altered by continued shifting of the meanders; the shortening effect of occasional cutoffs is cumulative only in the pages of Mark Twain's "Life on the Mississippi". That these local shortenings are compensated, over a period of years, by continued slow growth of all of the loops is indicated by the fact that, although 20 cutoffs between 1722 and 1884 shortened the Mississippi by about 249 miles, the river was by 1929 about the same as the original length (Pickels, 1941, p. 339).

Disturbance of equilibrium relations in the stream by sudden local shortenings and slow general lengthening are not inconsistent with the concept of grade as defined here. If a cutoff results in a "significant" break in the longitudinal profile the stream may be properly considered to be ungraded at that point; the height of the break that is "significant" depends simply on the point of view of the investigator. Schoklitsch's analysis of profile readjustments in the vicinity of a single cutoff, too long and not sufficiently pertinent to be summarized here, is an excellent illustration of readjustment on a small scale (1937, p. 153, 154; *see also* Shulits, 1936). The effect of a number of cutoffs was cited above, also from the engineering literature, to illustrate the very rapid headward propagation of a local steepening in the longitudinal profile. But in most cutoffs in streams flowing in alluvium the resulting steepening in the bed is less than its normal relief from bend to crossing, the break in the slope of the water surface is less than the difference between high and low water levels, and the increased velocity in the steepened part is less than the seasonal variation in velocity. Because breaks of this type usually leave no recognizable record in the valley-floor

features, they may in many types of geologic studies be properly neglected in considering whether the stream is graded. With other short-term fluctuations in velocity, discharge, and load, they are considered to be covered by the expression "over a period of years" which is an essential part of the definition of grade.

DEPOSITS OF GRADED AND AGGRADING STREAMS

The body of detritus that floors the valley of a graded stream usually consists of three types of material, unlike in origin: (1) sand and gravel originally carried as bed load and deposited in the shifting channel, (2) an overlying sheet of sand and silt deposited from suspension in slow moving or ponded overbank waters, and (3) detritus not directly related to the work of the main stream, as talus and slope wash from the valley sides, and loess and wind-blown sand.[8] The maximum potential thickness of the channel gravel sheet equals the maximum potential depth of scour in the shifting channel during high-water stages; a thickness of a few tens of feet does not necessarily indicate that the stream has aggraded or is aggrading. The maximum thickness attainable by the overbank silt is determined by the height to which it can be built by successive overspreadings of the valley floor by flood waters without long-term change in the river level; the natural levee, as such, is not an evidence of aggradation. There is no well-defined limiting thickness for deposits of type (3); for example, over 150 feet of fan wash accumulated over the main stream channel gravel sheet in the Shoshone Valley in Wyoming during a period when the Shoshone River was not aggrading (Mackin, 1937, Pl. 1, p. 827–833).

True aggradation, which involves a systematic long-term rise in the river level, may be effected by a thickening of deposits of types (1), (2), or (3), or any combination of them.

An aggrading stream may produce a thick fill that consists largely or wholly of channel deposits. Numerous examples occur in valleys marginal to glaciated ranges, where the fill was deposited by proglacial streams and subsequently trenched so that its internal structure can be seen; exposures in the frontal scarp of a great fill terrace in the Cle Elum Valley in Washington, for instance, show over 200 feet of uniformly bedded gravels. This preponderance of channel deposits certainly does not mean that the Pleistocene Cle Elum River carried no suspended load, nor does it mean that the successively higher valley floors formed during the period of aggradation carried no veneers of overbank silt.

Aggradation may, on the other hand, produce a fill made up largely of silt and lacustrine clay—the Oligocene White River deposits of the Great Plains are a case in point. The prevailing fine texture of the White River beds certainly does not represent the loads carried by the Oligocene streams; lenses and stringers of channel gravel, contrasting sharply with the overbank silts and clays, occur throughout the White River sediments (Osborn, 1929, p. 103–109).

The thick aggradational fill in the Kickapoo Valley in Wisconsin consists chiefly of slope wash derived from the local valley sides (Bates, 1939, p. 870–876). This is perhaps an exceptional case, but greater or less amounts of local wash, partly re-

[8] For a more elaborate classification of valley floor materials *see* Happ, Rittenhouse and Dobsen, 1940, p. 22–31.

worked and interfingering with main stream deposits, are to be expected in all valley fills.

Contrasts between aggradational fills of different types depend largely on contrasts in the rate of lateral shifting of the depositing stream relative to the rate of upbuilding of the deposit and, especially, on the mechanism of lateral shifting, whether by meander swing and sweep processes (Melton, 1936) or by avulsion as in the braided stream. These habits depend in turn on slope, discharge, load, channel characteristics, and the hydrographic regimen of the stream, resistance of the valley-floor materials to lateral cutting, vegetative cover on the valley-floor, distance from source of the detritus and from the mouth of the stream, relief and erosional processes on adjacent uplands, and other factors that cannot be evaluated here. The points to be made are simply: (1) that *deposits* formed by or associated with aggrading streams differ markedly from the *loads* carried by them, (2) that distinguishing between channel and overbank deposits is the first essential step in interpreting modern valley fills or ancient fluviatile sediments, and (3) that, even after this distinction is made it is virtually impossible to work directly from the grade sizes represented in the channel deposits to the characteristics of the depositing streams because there is no simple relationship between the deposits of an aggrading stream and such partly interdependent factors as slope, discharge, channel characteristics, velocity, and load. We cannot proceed directly from laboratory-determined laws relating to stream *transportation processes* to interpretation of ancient stream *deposits*. An alternative and promising route of attack on the problem is via study of deposits now being formed by natural streams of many types to determine whether the sum total of all of the characteristics of given deposits is uniquely related to the particular modern streams by which they are being formed, and to proceed thence to an understanding of the characteristics of ancient streams by comparison of their deposits with deposits of modern streams of known characteristics.

Here again, as in every phase of the study of streams, there is a broad field in which the interests of the geologist and the engineer overlap. For example, correct evaluation of the factors that control what proportion of overbank silts and channel gravels are incorporated in an aggrading valley fill under natural conditions may permit intelligent modification of these factors to alter, to the advantage of a reservoir, the ratio of bed load to suspended load in the debris charge delivered to the reservoir by the aggrading streams that enter it. The marked decrease in the rate of storage depletion in Lake Mac Millan brought about by accidental introduction and development of a dense growth of saltcedar (tamarisk) on the aggradational flood plain above the reservoir (Eakin and Brown, 1939, p. 17–18; Walter, in discussion of Taylor, 1929, p. 1722–1725) illustrates the effectiveness of modification of only one of the factors controlling silt deposition on the valley floor.

SECONDARY EFFECTS OF AGGRADATION

DECREASE IN SUPPLIED LOAD

Aggradation (for whatever reason) involves burial of the lower waste-shedding slopes of the valley sides, and a consequent reduction in the load supplied to the

stream system as a whole. Usually far more important, back-filling in valleys tributary to the aggrading trunk stream tends to reduce the load delivered by the tributaries. In the extreme case, aggradation by the main stream may so far outstrip upbuilding by its tributaries that the lower portions of their valleys are ponded; settling basins formed in this manner serve to entrap all or most of the clastic waste carried by the tributaries. (For examples, *see* Lobeck, 1939.) In general, decrease in load calls for decrease in the slope of the main stream.

DECREASE IN DISCHARGE

A stream flowing in a valley cut in rock normally carries most of the runoff from its drainage basin as surface discharge. But in an aggraded valley a considerable part of the runoff may pass through the detrital filling as underflow, with a consequent reduction in surface discharge available for the transportation of load. In general, decrease in discharge calls for an increase in declivity.

CHANGE IN CHANNEL CHARACTERISTICS

Aggradation often involves a shoaling and widening of the channel, and it may cause very marked changes in the stream's characteristics, as from a meandering to a braided habit. These changes usually tend to reduce the efficiency of the channel and therefore to require an increase in declivity.

GENERAL STATEMENT

Changes of the types listed above are more or less incidental results of the reaction (aggradation) of a stream to a given "primary" change in control. Since they, in turn, call for modifications in declivity, they may be regarded as "secondary" controlling factors. They operate especially during the period of aggradation, but they may continue to affect the stream long after it has readjusted itself to the new conditions. Thus, while certain "downvalley" changes in control (as rise of base level) do not directly call for change in slope, the eventual readjusted profile may, under different circumstances, be steeper or less steep than the original profile because of secondary chain-reaction effects. Any attempt to predict the final form or slope of the readjusted profile by evaluating the effects of a given man-made primary change in controls which fails to take into account these secondary changes in slope-controlling factors is liable to serious error. In general, the net effect on declivity of any primary change in control will be the algebraic sum of the parallel or opposed effects of the primary change and the associated secondary changes.

PROFILES OF ADJUSTED AND DISADJUSTED STREAMS

SORTING IN THE GRADED STREAM

As the velocity of the graded stream increases with seasonal increase in discharge, progressively coarser grains are set in motion up to the limits of the competence of the current and the supply of detritus available in the bed and banks. As velocity decreases with passing of the high-water stage, the materials in motion are thrown down

in order of decreasing grain size. Every part of the channel deposit that veneers the valley floor is worked over again and again as the stream shifts laterally, each time with selective deposition of the coarser materials and a winnowing out of the fines. For this reason the valley-floor channel deposits in any part of the valley contain notably higher proportions of coarse materials than the bed load in transit through that segment of the valley in any representative period of time. There is, in this sense, a sorting process in operation in the graded stream.

Because the finer grains in the bed load are set in motion earlier, move faster while in motion, and are retained in motion longer during each seasonal fluctuation in discharge, there is a "running ahead of the fines" in the channel of the graded stream. But this "running ahead of the fines" does not cause a downvalley decrease in the caliber of the load handled by the stream. The fines move faster toward and into any given segment, but they also move faster through and away from that segment; the average grain size in the bed load moving through any segment is the same as though all the grain sizes moved at the same rate. The primary cause of the downvalley decrease in caliber of load in the graded stream is attrition, not sorting.

The same conclusion holds for the channel gravel sheet which veneers the valley floor. Every boulder or pebble that is lodged in the valley-floor alluvium in any segment of the valley at any period of time is likely to be moved and lodged again farther downvalley in successive intervals of time. Downvalley decrease in the grain sizes making up the channel gravel sheet is due, not to sorting, but to attrition during stages of movement in the channel, possibly accentuated by weathering during periods of lodgement.

SORTING IN THE AGGRADING STREAM

It has been noted earlier that aggradation may be effected either by a downvalley movement of a wave or waves of steepened declivity, or by an upvalley propagation of a wave or waves of flattened declivity. The essential relationship in both cases is that of a given segment shedding debris into an adjacent (downvalley) segment that is not quite adjusted to the transportation of that debris. Under these circumstances the operation of the seasonally expanding and contracting channel combines with a deficiency in velocity to assure that the coarsest fractions of the load entering any disadjusted segment will be deposited in that segment. Since the channel of the stream is raised as aggradation proceeds, the materials so deposited will not be subject to reworking and continued downvalley movement. There is in the aggrading stream, in other words, a "permanent withdrawal from circulation" of the coarser fractions of the bed load, and the "running ahead of the fines" in this case makes for a real and substantial downvalley decrease in the caliber of the load in transit, and in the materials deposited by the stream as it aggrades.

EXCHANGE IN GRADED AND AGGRADING STREAMS

The channel of the graded stream, shifting back and forth in a valley-floor gravel sheet made up largely of channel deposits which may be somewhat coarser than the average bed load in transit, has little chance to decrease the caliber of its load by the

process of exchange. But the channel of the aggrading stream may shift laterally in alluvium consisting essentially of contemporaneous overbank deposits. In this case the materials added to the load of the stream by scour and caving at the outside of a shifting bend may be largely fine silts and sands, but the coarser fractions of the bed load supplied from upvalley tend to be deposited and left behind as the channel shifts. The term exchange as used here does not imply any equivalence in weight or bulk of the material set in motion and deposited; the stream simply cuts at the outside of its bends because inertia normally holds the strongest current against the outside bank; it deposits the coarsest fractions of the load in transit on its channel floor with every seasonal fluctuation and leaves some of these deposits behind as the channel shifts. In the aggrading stream, in contrast to the graded stream, this type of exchange may result in a notable downvalley decrease in the caliber of load in transit.

EFFECT OF DOWNVALLEY CHANGE IN CALIBER OF LOAD ON THE FORM OF THE PROFILE

It has been repeatedly emphasized that the declivity of the graded stream is controlled by load (and other factors); the declivity is adjusted to furnish just the velocity required for the transportation of all the load supplied to the stream. In the aggrading stream the supplied load does not control declivity in the same degree because, by definition, *all* of the supplied load is not transported. But it is important to recognize that the amount of material moved through any segment of the channel of the aggrading stream in any interval of time is enormously greater than the amount deposited, and that even in the aggrading stream the declivity of each segment is *approximately* adjusted to the load in transit through that segment. In general, with decrease in the discrepancy between the supplied load and the load in transit, the aggrading stream approaches the graded condition.

No generalization can be made with regard to the average steepness of the profiles of graded and aggrading streams as such; both may vary from a small fraction of a foot to hundreds of feet per mile. But an exceedingly useful generalization can be made with regard to a contrast in the *form* of the profiles of graded and aggrading streams. Since declivity is in general adjusted to caliber of load in transit, and since the downvalley decrease in caliber of load in aggrading streams (by attrition, sorting, and exchange) is much more rapid than the downvalley decrease in caliber of load in graded streams (by attrition), it follows that declivity should decrease in a downvalley direction much more rapidly in the aggrading stream than in the graded stream under otherwise similar conditions. The profile of aggradation should be, in other words, more strongly "concave upward" than the graded profile. Thus, while the profile of the graded stream usually shows no tendency to be asymptotic with respect to a horizontal plane passing through a downvalley control point, the profile of the aggrading stream should and usually does show a definite tendency in this direction.

The writer has found two "rules" that follow from the discussion above to be useful tools in field study and interpretation of terraces of many types in stream valleys: (1) If there is any considerable length of stream upvalley from a given segment, aggradational channel deposits in that segment are so consistently finer in grain size than earlier or later deposits formed when the stream was at grade that variation in grain size and sorting serves as a criterion, for example, in distinguishing

between channel deposits laid down in a valley-filling stage and the channel gravel sheet that mantles terraces cut in the fill during a subsequent degradational stage. (2) Aggradational profiles (recorded by terrace remnants) are usually steeper than earlier or later graded profiles in the upper parts of proglacial valleys, but the contrast in slope decreases in a downvalley direction and may be reversed, so that the aggradational profile is less steep than the graded profile in the vicinity of a downvalley control point.

CONCLUSIONS

"Let us suppose that a stream endowed with a constant volume of water, is at some point continuously supplied with as great a load as it is capable of carrying. For so great a distance as its velocity remains the same, it will neither corrade (downward) nor deposit, but will leave the slope of its bed unchanged. But if in its progress it reaches a place where a less declivity of bed gives a diminished velocity, its capacity for transportation will become less than the load and part of the load will be deposited. Or if in its progress it reaches a place where a greater declivity of bed gives an increased velocity, the capacity for transportation will become greater than the load and there will be corrasion of the bed. In this way a stream which has a supply of debris equal to its capacity, tends to build up the gentler slopes of its bed and cut away the steeper. It tends to establish a single uniform slope. . . ."

"Every segment is a member of a series, receiving the water and waste of the segment above it, and discharging its own water and waste upon the segment below. If one member of the series is eroded with exceptional rapidity, two things immediately result; first, the member above has its level of discharge lowered, and its rate of erosion is thereby increased; and second, the member below, being clogged with an exceptional load of detritus, has its rate of erosion diminished. The acceleration above and the retardation below, diminish the declivity of the member in which the disturbance originated; and as the declivity is reduced the rate of erosion is likewise reduced.

"But the effect does not stop here. The disturbance which has been transferred from one member of the series to the two which adjoin it, is by them transmitted to others, and does not cease until it has reached the confines of the drainage basin. For in each basin all lines of drainage unite in a main line, and a disturbance on any line is communicated through it to the main line and thence to every tributary. And as any member of the system may influence all the others, so each member is influenced by every other. There is interdependence throughout the system."

These paragraphs, taken with minor changes in wording from the Henry Mountain report, dated 1877, set forth the essence of Gilbert's idea of grade in streams; additions and modifications discussed in the present paper are chiefly matters of qualifying detail. The principal conclusion, that the concept of the graded stream as a system in equilibrium is valid, is based on:

(1) Citation of broad valley floors cut by long-continued planation at the same level by high-gradient streams crossing rock types of varying resistance to corrasion;

(2) Analysis of the form of the longitudinal profile developed and maintained by the graded stream under stable conditions, demonstrating by citation of cases that, in each segment, slope is adjusted to provide, with available discharge and under prevailing channel conditions, just the velocity required for transportation of all of the load supplied to that segment without regard for variation in resistance to corrasion in the subjacent materials; and,

(3) an outline of the manner in which graded streams readjust themselves to natural and man-made changes in controlling conditions of several types, demonstrating that the stream responds to such changes always so as to "absorb the effect of the stress", and thus exhibits the chief and diagnostic characteristic of the equilibrium system.

A critical point in connection with (2) is that, because in a trunk stream conditions

controlling slope do not vary systematically from segment to segment, the longitudinal profile cannot be a simple mathematical curve. This conclusion is qualitative; if, in conformity with it, we cease to smooth out real departures from uniformity and center the attack on them, with an adequate understanding of the genetic relationships of the independent and interdependent factors involved, then mathematical analysis of longitudinal profiles will advance our knowledge of streams.

A second generalization, important because it has been so generally neglected in geologic writings, is that the slope of the graded profile is adjusted to, or controlled by, not only the classic "load and discharge" but also the cross-sectional form and alignment of the channel—the more efficient the channel, the lower the slope.

In connection with (3) the present study tends to confirm the standard geologic view that streams readjust themselves to new conditions primarily by adjustments in slope, and only in minor degree by modification of the channel section. This statement is so phrased as to avoid any semblance of a "law"—certainly no fetish attaches to slope, and each individual case must be judged on the basis of the evidence. But it does appear that, confronted by changed conditions that call for increased or decreased energy for transportation, the stream usually responds by increasing or decreasing its total energy by appropriate adjustments in slope rather than by effecting economies in the energy dissipated in friction.

Additional generalizations include the distinction between "upvalley" and "downvalley" changes in control and between "upvalley" and "downvalley" reactions of the stream to a given change, the contrast between the form of the disadjusted profile during the period of readjustment and the final readjusted profile, and the effect of secondary changes in control on the slope of the readjusted profile.

With a few minor lapses, this paper does not treat the practical implications of the concept of grade. In geology these ramify widely, ranging from the power of rivers to corrade laterally to interpretation of ancient fluvial sediments and the origin of unconformities beneath and within them. In connection with control of rivers by men, a safe general implication is that the engineer who alters natural equilibrium relations by diversion or damming or channel-improvement measures will often find that he has a bull by the tail and is unable to let go—as he continues to correct or suppress undesirable phases of the chain reaction of the stream to the initial "stress" he will necessarily place increasing emphasis on study of the genetic aspects of the equilibrium in order that he may work *with* rivers, rather than merely *on* them. It is certain that the long-term response of streams to the operations of the present generation of engineers will provide much employment for future generations of engineers and lawyers.

In this connection the most important point brought out by the study may well be the striking analogy between the streams' response to the works of man and to accidents and interruptions due to geologic causes. Nature has brought to bear on streams nearly all of the changes in controlling conditions that are involved in modern engineering works; the record of the long-term reaction of rivers to past geologic changes that is revealed by terraces and in dissected valley fills should contribute much to an understanding of the future of streams that man seeks to control, and will call for changes in design. Conversely, every advance in knowledge of erosional,

transportation, and sedimentation processes deriving from engineering investigations will increase the geologist's ability to interpret the record of the past. As the engineer becomes more and more concerned with the genetic aspects of his especial problems (as he must), and as the geologist learns more about the quantitative aspects of his especial problems (as *he* must), it will become evident that the problems are in large measure the same. As Rubey (1931b) puts it, there is "a need for close cooperation among *students of stream-work*."

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